INFLIGHT ESTIMATION OF MAGNETOMETER BIASES FOR THE ACTIVE MAGNETOSPHERIC PARTICLE TRACER EXPLORERS (AMPTE) MISSION

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ABSTRACT

This document presents an analysis and the simulated test results of two algorithms, RESIDT and RESIDG, which were developed to estimate the residual biases for an orthogonal triad of magnetometers. The algorithms were tested under the simulated flight conditions of the Active Magnetospheric Particle Tracer Explorers (AMPTE) mission for sensitivity to data rate, sensor granularity, orbit position, magnitude of residual bias, and sensor misalignment. On the basis of these test results, conclusions were drawn concerning the type of data necessary to ensure good algorithm performance.

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SECTION 1 - INTRODUCTION

1.1 OVERVIEW

Experience in attitude determination using magnetic field measurements has shown that the inflight calibration of magnetometers is essential to meeting attitude accuracy requirements in the error range of 2 to 3 degrees (Reference 1). This document presents the results of the tests of two algorithms, RESIDT and RESIDG, which were developed to estimate the residual biases for an orthogonal triad of magnetometers under the simulated flight conditions of the Active Magnetospheric Particle Tracer Explorers (AMPTE) mission.

The RESIDT algorithm was developed by Computer Sciences Corporation (CSC) specifically for this study. The technical details of its formulation are discussed in detail in this report. The RESIDG algorithm was developed for a previous mission; the computer code was extracted from that of the Solar Maximum Mission (SMM). RESIDG is the only piece of previously existing software that is attitude-independent and suitable for AMPTE, and which has a code that is adaptable and thoroughly modularized.

Section 2 presents a general formulation of the inflight residual bias determination problem. Sections 3 and 4 discuss the RESIDT and RESIDG algorithms in relation to the general formulation. Section 5 discusses the orbital conditions and attitude constraints assumed for this study and the results of the AMPTE Engineering Simulator (Reference 2) runs. In addition, some observations based on that data are presented. Section 6 presents the tests made to simulate the effects of items such as data period, sensor granularity, and sensor misalignment, and includes the test results. Section 7 presents the conclusions that are evident from the results of this study.

1.2 AMPTE MISSION

The AMPTE mission is a small Explorer-class international cooperative program between the Bundesministerium fuer Forschung und Technologie (BMFT) of the Federal Republic of Germany (FRG) and the National Aeronautics and Space Administration (NASA). Two spacecraft, the Charge Composition Explorer (CCE), which is provided by NASA, and the Ion Release Module (IRM), which is provided by the FRG, will investigate the detailed physical processes operating within the magnetosphere-ionosphere domain using active experimentation (Reference 3). The concept involves the release, by the IRM, of tracer ions outside the magnetosphere and within the solar wind at the subsolar point as well as at various other points, including the magnetospheric tail, while the highly eccentric IRM orbit precesses. The CCE instrumentation will detect released ions inside the magnetosphere and will perform other charge-detection experiments independent of ion releases (Reference 3).

Only the attitude determination subsystem and planned orbital conditions of the CCE are addressed in this document. The CCE will be injected into a highly eccentric orbit with perigee altitude of 300 kilometers and apogee attitude of 7.5 Earth radii (Reference 3). The spacecraft attitude will be spin stabilized, and the CCE will carry a digital Sun sensor and a three-axis orthogonal magnetometer triad. The spin axis will lie in the orbital plane, and the angle between the spin axis and the Sun line will be minimized.

SECTION 2 - EQUATIONS FOR MAGNETOMETER BIAS DETERMINATION

Development of a formalism that is independent of spacecraft attitude requires a loss function that is independent of spacecraft attitude. A loss function that satisfies this criterion is described in this section.

The quantities used throughout this section are defined as follows:

$H_j^{(i)}$ = jth component of the model magnetic field in the geocentric inertial (GCI) system at position i

$M_j^{(i)}$ = jth magnetometer reading at position i

B_j = jth magnetometer bias which is taken to be independent of the spacecraft position

For the ith point, an error $\delta^{(i)}$ is defined by the following equation:

$$\delta^{(i)} = \vec{H}^{(i)2} - \vec{M}^{(i)2} - \vec{B}^2 + 2\vec{M}^{(i)} \cdot \vec{B} \qquad (2\text{-}1)$$

The objective of this equation is to minimize quantity $\delta^{(i)}$ by adjusting the bias vector B to its optimal value. Thus, the loss function to be minimized is given by

$$L(\vec{B}) = \sum_{i=1}^{N} \omega^{(i)} \delta^{(i)2} \qquad (2\text{-}2)$$

where $\omega^{(i)}$ = the weight associated with the ith data point.

The weights are assumed to be normalized to unity, that is

$$\sum_{i=1}^{N} \omega^{(i)} = 1 \qquad (2\text{-}3)$$

Determining the minimum value of $L(\vec{B})$ first requires that its derivatives with respect to the components of the bias vector be set equal to zero:

$$\frac{\partial L}{\partial B_\alpha} = 0 \tag{2-4}$$

where

$$\frac{\partial L}{\partial B_\alpha} = -4 \sum_{i=1}^{N} \omega^{(i)} \left[\vec{H}^{(i)\,2} - \left(\vec{B} - \vec{M}^{(i)} \right)^2 \right] \left(B_\alpha - M_\alpha^{(i)} \right) \tag{2-5}$$

Combining Equations (2-3), (2-4), and (2-5) leads to the following result:

$$\sum_{k=1}^{3} O_{\alpha k} B_k = b_\alpha + F_\alpha(\vec{B}) \tag{2-6}$$

where

$$O_{\alpha k} = \delta_{\alpha k} (\langle H^2 \rangle - \langle M^2 \rangle) - 2 \langle M_\alpha M_k \rangle$$

$$b_\alpha = \langle M_\alpha H^2 \rangle - \langle M_\alpha M^2 \rangle$$

$$F_\alpha(\vec{B}) = (\vec{B}_\alpha - \langle M_\alpha \rangle) \vec{B}^2 - 2 B_\alpha \vec{B} \cdot \langle \vec{M} \rangle$$

$$\langle A \rangle = \sum_{i=1}^{N} \omega^{(i)} A(i)$$

$$\delta_{\alpha k} = 1 \text{ if } k = \alpha; = 0 \text{ if } k \neq \alpha$$

Equation (2-6) can be solved directly to obtain the best value for the bias vector $\vec{B}$.

SECTION 3 - RESIDG ALGORITHM

3.1 GENERAL DESCRIPTION

RESIDG is an attitude-independent method for determining residual magnetometer biases for an orthogonal magnetometer triad flown onboard a spacecraft. Reference 4 contains a detailed mathematical description of RESIDG.

RESIDG minimizes the loss function given in Equation (2-2). In Equation (2-1), only the magnetic field components are treated as independent parameters. The resulting problem, a least-squares fit to a quadratic equation, is solved by using an iterative procedure which converges to the exact solution if the biases are much smaller than the magnetometer readings themselves.

RESIDG approaches the solution to the problem in two steps. First, RESIDG obtains a trial solution for the biases. Then, RESIDG iterates a linearized form of Equation (2-6) until a precise solution is obtained.

The trial solution is determined by minimizing the following loss function:

$$L'(\vec{B}) = L(\vec{B}) - \langle \delta(\vec{B}) \rangle^2 \qquad (3\text{-}1)$$

where

$$\langle \delta(B) \rangle = \sum_{i=1}^{N} \omega^{(i)} \delta^{(i)}(B)$$

$o^{(i)}(\vec{B})$ is given by Equation (2-1) and $L(\vec{B})$ is the loss function given by Equation (2-2). The equations for $\vec{B}$, which result when $L(\vec{B})$ is minimized, are linear in B and, therefore, are simpler to solve. When the magnetometer data

is ideal (i.e., no noise or measurement error exists), $\langle \delta(\vec{B}_T) \rangle = 0$, where $\vec{B}_T$ is the true bias. In this case, $L'(\vec{B}_T) = L(\vec{B}_T) = 0$ and the same value of B minimizes both $L'(\vec{B})$ and $L(\vec{B})$. The solution to the linear problem, therefore, is precisely the same as the solution to the non-linear problem, and the trial solution is exact.

A problem arises with this process when noise and inexact measurements are present in the data. In those cases, the loss functions $L'(\vec{B})$ and $L(\vec{B})$ will, in general, be minimized by quite different values of $\vec{B}$. The trial solution will be completely different from the true solution. This is illustrated theoretically in Reference 4 and experimentally with real spacecraft data (Reference 1). Thus, in general, it should be expected that the RESIDG trial solution will be quite different from the actual least-squares solution with real data.

After the trial solution is obtained, RESIDG then linearizes Equation (2-6) and uses a Newton-Raphson scheme with the trial function described previously as a first guess to obtain a solution. Convergence is defined as the point at which the input and output values agree to within a present tolerance.

3.2 EXISTING SOFTWARE

The RESIDG algorithms are implemented in a set of several FORTRAN subroutines, which are invoked by a call to the main subroutine RESIDG. For this study, the RESIDG software was obtained from the ground-support software for the SMM, for which it was used for inflight determination of biases for the SMM magnetometers (Reference 3). To facilitate interfacing, the SMM routine MAGBAS also was retained, because all the arrays and parameters were set up essentially as they were needed for this study. However, task personnel

did develop a driver routine to provide the necessary program functions for exercising the existing software (Section 6.1).

Figure 3-1 is a block diagram of the RESIDG routines as implemented in this study. Reference 3 describes the calling sequences and other features of the RESIDG software.

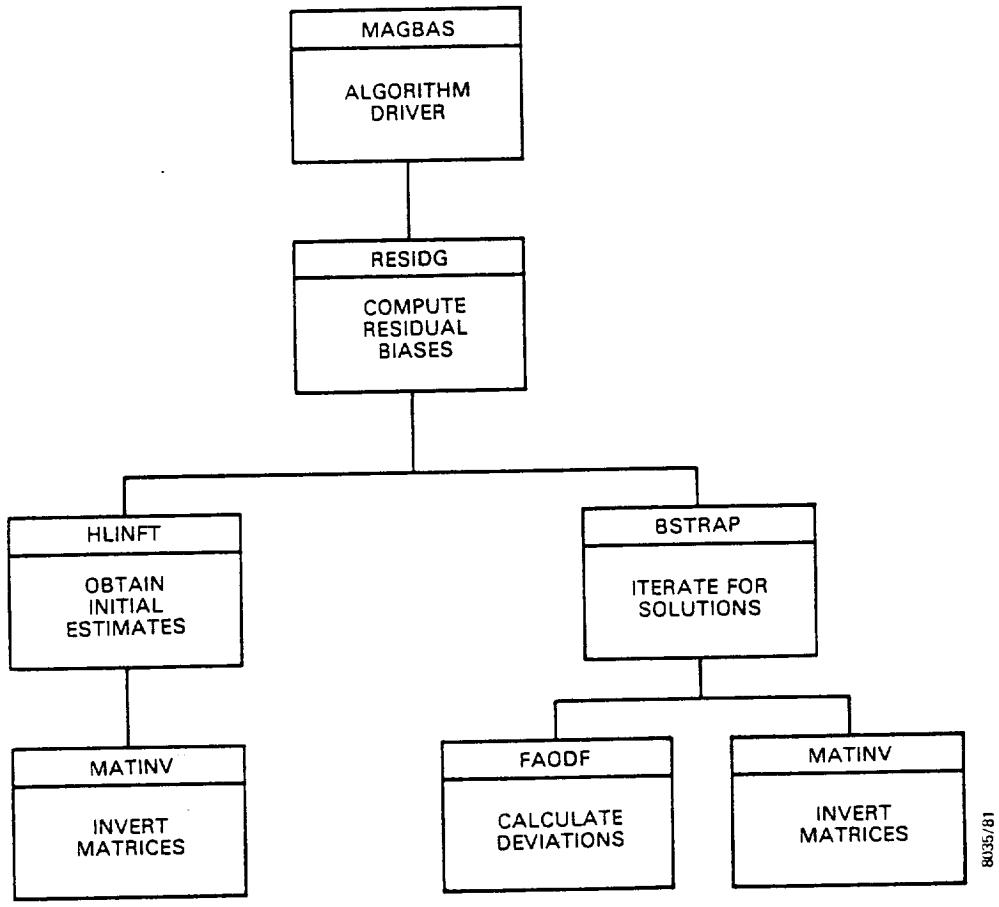

Figure 3-1. RESIDG Software Calling Hierarchy

SECTION 4 - RESIDT ALGORITHM

4.1 GENERAL DESCRIPTION OF THE ITERATIVE SOLUTION

Equation (2-6) is nonlinear in terms of the bias vector. In general, an analytic solution to this type of equation is not available; however, the construction of a numerical solution is possible.

The method chosen during this study to the solution to Equation (2-6) is an iterative procedure. The zero-th order, or trial solution to Equation (2-6), is obtained by dropping the nonlinear terms in comparison to the linear terms. This approximation is valid only when the bias is small in comparison with the actual magnetic field. This point is not critical, as the iteration scheme constructs an accurate solution even when the trial solution is not close to the true solution. The trial solution is given by

$$B_k^{(0)} = \sum_{\alpha=1}^{3} (O^{-1})_{k\alpha} b_\alpha \qquad (4\text{-}1)$$

where O^{-1} = inverse of the matrix O

$B_k^{(0)}$ = trial solution

This solution may be iterated as follows:

$$B_k^{(1)} = B_k^{(0)} + \sum_{\delta=1}^{3} (O^{-1})_{k\delta} F_\delta (\vec{B}^{(0)})$$

$$\vdots \qquad (4\text{-}2)$$

$$B_k^{(j)} = B_k^{(0)} + \sum_{\delta=1}^{3} (O^{-1})_{k\delta} F_\delta (\vec{B}^{(j-1)})$$

The iteration continues until

$$\text{ABS}\left(\frac{B_k^{(j)} - B_k^{(j-1)}}{B_k^{(j)}}\right) < \varepsilon \qquad (4\text{-}3)$$

where ε = some arbitrarily small value depending on the accuracy desired.

4.1.1 CONVERGENCE PROPERTIES

The investigation of the convergence properties of the iterative solution given by Equation (4-2) requires the analysis of a related problem. Consider a scalar field $H^{(i)}$ which is determined from a field model at position i. The corresponding measured field is $M^{(i)}$, and the bias to be determined is denoted by B. The analogous loss function to that given by Equation (2-2) is

$$L(B) = \sum_{i=1}^{N} \omega^{(i)} \delta^{(i)2} \qquad (4\text{-}4)$$

where

$$\delta^{(i)} = H^{(i)2} - M^{(i)2} - B^2 + 2M^{(i)}B \qquad (4\text{-}5)$$

The resulting equation, whose solution minimizes the loss function of Equation (4-4), is given by

$$OB = b + F(B) \qquad (4\text{-}6)$$

where

$$O = \langle H^2 \rangle - 3\langle M^2 \rangle$$

$$b = \langle H^2 M \rangle - \langle M^3 \rangle$$

$$F(B) = B^3 - 3B^2 \langle M \rangle$$

The nth iterative solution to Equation (4-6) is written as

$$B^{(n)} = B_{TRUE} + \varepsilon_n \qquad (4\text{-}7)$$

where B_{TRUE} = the exact solution to Equation (4-6)
ε_n = the error of the iterative solution after n iterations

Combining Equations (4-6) and (4-7) leads to the following result:

$$O\varepsilon_{n+1} = \frac{\partial F}{\partial B} \varepsilon_n \qquad (4\text{-}8)$$

where

$$\frac{\partial F}{\partial B} = 3B(B - 2\langle M \rangle) \qquad (4\text{-}9)$$

Thus, the ratio of successive errors is

$$\frac{\varepsilon_{n+1}}{\varepsilon_n} \cong \frac{3B(B - 2\langle M \rangle)}{\langle H^2 \rangle - 3\langle M^2 \rangle} \qquad (4\text{-}10)$$

Two limits to Equation (4-10) should be considered. First, in the case, $B/H \ll 1$, Equation (4-10) reduces to

$$\frac{\varepsilon_{n+1}}{\varepsilon_n} \cong \frac{3B\langle H \rangle}{\langle H^2 \rangle} \qquad (4\text{-}11)$$

Equation (4-11) indicates rapid convergence of the iterative solution, because $\varepsilon_{n+1}/\varepsilon_n$ is of the order B/H which has been assumed to be small.

For B>>H, then, Equation (4-10) reduces to

$$\frac{\varepsilon_{n+1}}{\varepsilon_n} = 1 \qquad (4\text{-}12)$$

For this case, the solution would converge very slowly.

Equation (4-10) yields only qualitative results for the real three-dimensional magnetometer bias determination problem; however, it is expected that the general conclusions will be valid as illustrated by Equations (4-11) and (4-12).

4.1.2 SPECIFIC EXAMPLE OF CONVERGENCE

The AMPTE engineering data simulator (Reference 2) was used to generate biased magnetometer data to investigate the convergence properties of RESIDT. Two cases were considered in approximating the limiting values discussed in Section 4.1.1--B/H<<1 and B/H>>1.

The first case considered was B/H<<1; in this case, 200 data points were included in the calculation. Data that included the perigee point at which the magnetic field attains its maximum value was used. The magnetic field can be resolved into a component along the AMPTE spin axis, $H_{||}$, and a component perpendicular to the spin axis, $H_{\perp}$. The maximum or perigee values for these components are $H_{\perp}^{MAX}$ = 240 milligauss (mG) and $H_{||}^{MAX}$ = 90 mG. The input biases are 5 mG, 10 mG, and 15 mG along the x, y, and z spin axes, respectively. The results of the bias determination calculation using RESTDT are shown in Table 4-1.

Rapid convergence and very high accuracy is obtained. The trial solution $B^{(0)}$, which corresponds to iteration 0 in

Table 4-1. Bias Determination Calculation for B/H << 1

ITERATION NUMBER	LOSS FUNCTION	B_x (mG)	B_y (mG)	B_z (mG)
0	54621.0	5.00288	12.0278	15.0213
1	5153.0	4.98344	9.38109	14.9473
2	370.0	5.00481	10.1647	15.0152
3	29.0	4.99870	9.95352	14.9959
4	2.0	5.00037	10.0128	15.0012
5	0.2	4.99990	9.99635	14.9997
6	0.01	5.00003	10.0009	15.0001

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NOTES:

NUMBER OF DATA POINTS = 200

$H_{\perp}^{MAX}$ = 240 mG

$H_{\parallel}^{MAX}$ = 90 mG

TRUE BIASES:

B_x (mG) = 5

B_y (mG) = 10

B_z (mG) = 15

Table 4-1, initially was not accurate in the y component and needed to be iterated to obtain satisfactory results.

Investigation of the case in which B>>H uses a subset of the data used in the first test. Here, 100 data points well outside the perigee region are used. For this test, $H_{\perp}^{MAX}$ = 5 mG and $H_{||}^{MAX}$ = 2 mG. As before, the input biases are 5 mG, 10 mG, and 15 mG. These results are presented in Table 4-2 and Figure 4-1. In this case, convergence is very slow and incomplete, as predicted in Section 4.1.1.

4.1.3 EQUATIONS FOR BIAS UNCERTAINTIES

The square of the magnitude of the computed magnetic field at point i is given by

$$g^{(i)} = M^{(i)^2} + B^2 - 2\vec{M}^{(i)} \cdot \vec{B} \qquad (4\text{-}13)$$

The error covariance matrix P_{ik}^{g} is

$$P_{ik}^{g} = \frac{\partial B_k}{\partial g^{(i)}} \qquad (4\text{-}14)$$

The relation between the computed magnetic field uncertainty $\delta g^{(i)}$ and the uncertainty in the bias δB_k is

$$\delta B_k = \sum_{i=1}^{N} P_{ik}^{g} \delta g^{(i)} \qquad (4\text{-}15)$$

Using Equation (4-13), the covariance matrix may be evaluated as follows:

$$P_{ik}^{g} = \frac{1}{2\left(B_k - M_k^{(i)}\right)} \qquad (4\text{-}16)$$

Table 4-2. Bias Determination Calculation for B>>H

ITERATION NUMBER	LOSS FUNCTION	B_x (mG)	B_y (mG)	B_z (mG)
0	24100.0	1.8	2.8	5.3
10	1460.0	3.7	5.5	11.0
20	501.0	4.1	6.1	12.4
30	240.0	4.4	6.3	13.1
40	133.0	4.5	6.5	13.6
50	81.0	4.6	6.6	13.9

8035/81

NOTES:

NUMBER OF DATA POINTS = 100

$H_{\perp}^{MAX}$ = 5 mG

$H_{\parallel}^{MAX}$ = 2 mG

TRUE BIASES:

B_x (mG) = 5

B_y (mG) = 10

B_z (mG) = 15

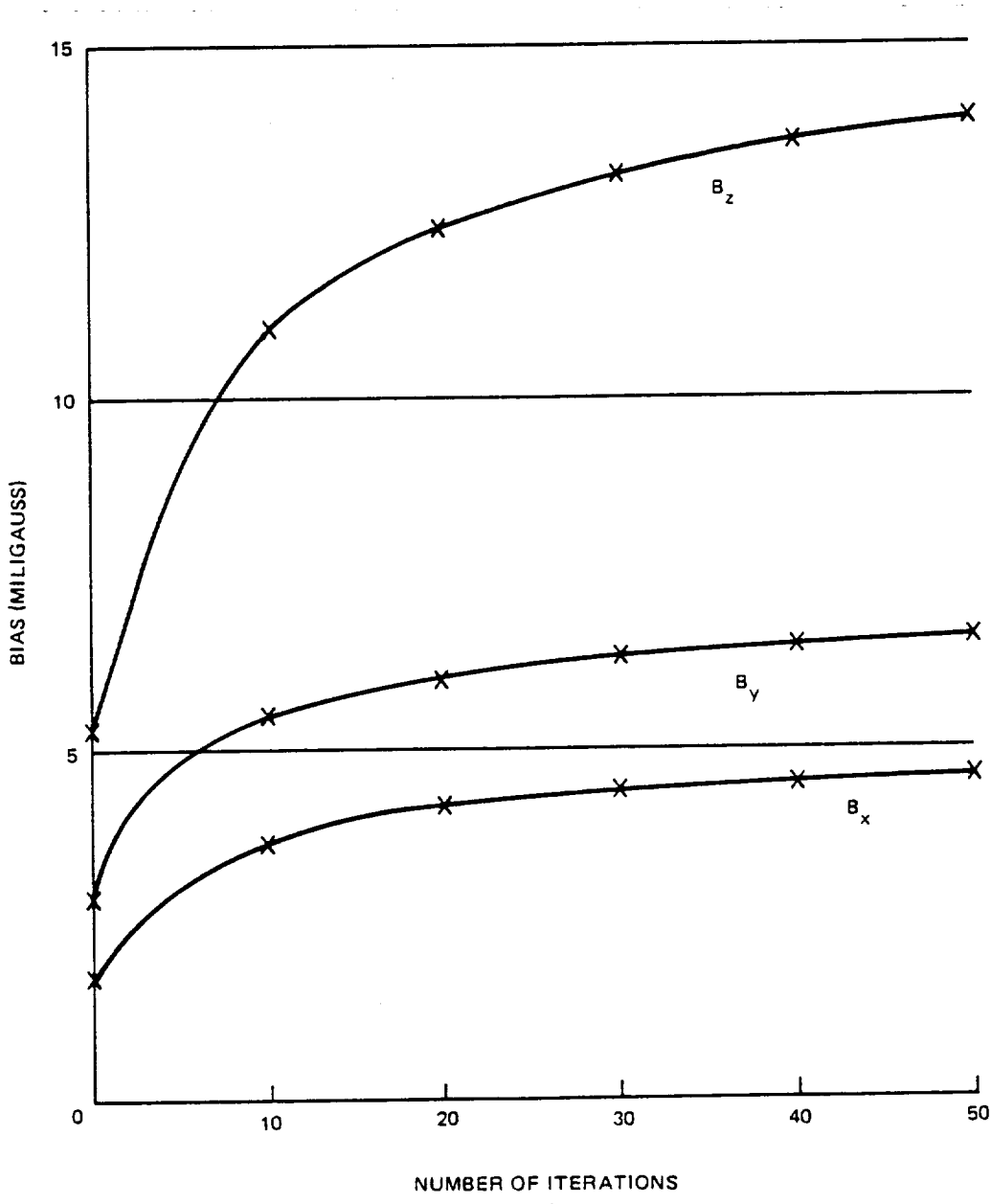

Figure 4-1. RESIDT Bias Solutions as a Function of Numerical Iterations

The quantity $\delta g^{(i)}$ is related to the uncertainty in the magnetometer reading $\delta M_\lambda^{(i)}$ by

$$\delta g^{(i)} = \sum_{\lambda=1}^{3} P_{i\lambda}^{M} \delta M_\lambda^{(i)} \tag{4-17}$$

where

$$P_{i\lambda}^{M} = \frac{\partial g^{(i)}}{\partial M_\lambda^{(i)}} = -2 \left(B_\lambda - M_\lambda^{(i)} \right) \tag{4-18}$$

The mean square uncertainties are related by

$$\delta g^{(i)\,2} = \sum_{\lambda=1}^{3} \left(P_{i\lambda}^{M} \right)^2 \delta M_\lambda^{(i)\,2} \tag{4-19}$$

It is assumed that $\delta M_\lambda^{(i)} = \delta M_\lambda$ (i.e., the uncertainty in the magnetometer reading) is independent of component and position. Therefore, the following result is obtained:

$$\delta g^{(i)\,2} = 4 g^{(i)} \delta M^2 \tag{4-20}$$

Using Equations (4-14), (4-16), and (4-20), the final result is given by

$$\delta B_k = \delta M \left(\sum_{i=1}^{N} \frac{g^{(i)}}{\left(B_k - M_k^{(i)} \right)^2} \right)^{1/2} \tag{4-21}$$

Equation (4-21) shows that if the bias components are comparable to the measurement, large uncertainties in the resulting biases will result.

4.2 SOFTWARE DESCRIPTION

Like RESIDG, the RESIDT algorithm is a collection of FORTRAN-callable subroutines (Figure 4-2). RESIDT is invoked by a call to subroutine RESIDT, with the other routines generally being transparent to the user. The following table describes the call argument parameters. These parameters appear in the table in the order in which they would be placed in an actual call to the routine.

Name	Type	I/O	Description
FLDSQD(1)	R*8	I	Magnitude of the model magnetic field squared (mG^2)
FLDMES(I,J)	R*8	I	The Jth component of the measured field (mG) at position I. The I index is dimensioned to NDIM and the J index is dimensioned to three
NDIM	I*4	I	Row dimension of FLDMES (NDIM,3)
NGOOD	I*4	I	Number of actual data points
ANOISE	R*8	I	Magnetometer noise level (mG)
EPS	R*8	I	Convergence parameter for iterative solution determined by BIASCL
ITERMX	I*4	I	Maximum number of iterations in BIASCL
IDEBUG	I*4	I	If IDEBUG = 0, no debug printout is written
IOUT	I*4	I	FORTRAN unit number for debug output
BIAS(3)	R*8	O	Computed biases (mG)
WEIGHT(1)	R*8	O	Computer normalized weights
IERR	I*4	O	Return code for BIASCL

Table 4-3 shows the core requirements in an IBM S/360-95 computer for both RESIDG and RESIDT.

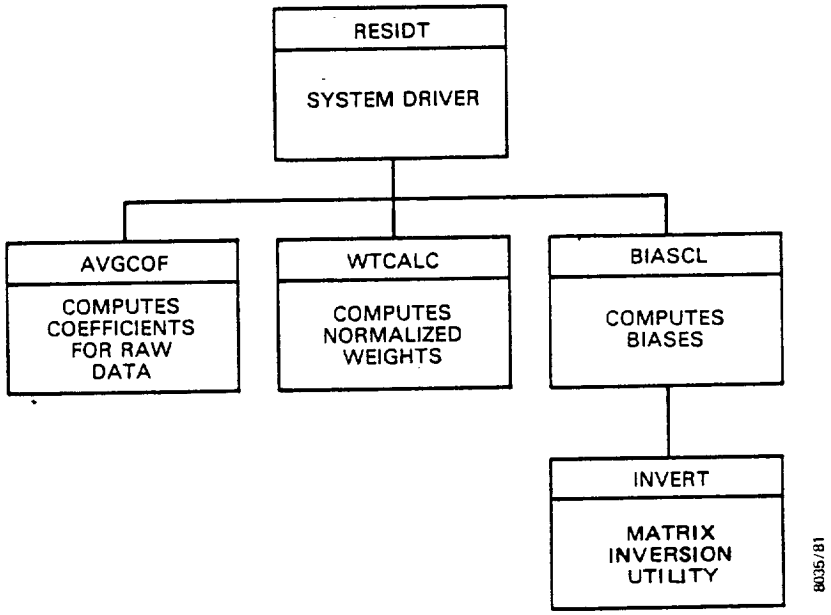

Figure 4-2. RESIDT System Baseline Diagram

Table 4-3. Core Requirements for RESIDT and RESIDG Modules

RESIDT MODULE		RESIDG MODULE	
SUBROUTINE	CORE REQUIREMENT (BYTES)*	SUBROUTINE	CORE REQUIREMENT (BYTES)*
RESIDT	0.92K	RESIDG	7.0K
WTCALC	0.63K	HLINFT	3.7K
AVGCOF	2.3K	BSTRAP	3.6K
BIASCL	1.9K	FAODF	0.36K
INVERT	1.7K	MATINV	1.5K
	7.5K (TOTAL)		16.2K (TOTAL)

*DATA ARRAYS ARE DIMENSIONED FOR 200 POINTS

SECTION 5 - AMPTE ENGINEERING SIMULATOR RUNS

This section describes the orbital conditions and attitude constraints assumed for the purpose of this study and the general results of the AMPTE simulator runs.

5.1 SPACECRAFT EPHEMERIS

The Keplerian orbital elements needed in this study are as follows (Reference 2):

- Semimajor axis--30446.2 kilometers
- Eccentricity--0.780657
- Inclination--0.0 degrees
- Argument of perigee--90.0 degrees
- Right ascension of the ascending node--90.0 degrees
- Mean anomaly--320.0 degrees
- Epoch (YYMMDD.HHMMSS)--830901.000000

In this configuration, the major axis of the elliptical orbit lies approximately along the projection of the Earth/Sun line on the orbit planes with apogee toward the Sun.

5.2 GEOMAGNETIC FIELD SIMULATION RESULTS

Figure 5-1 contains two pages of a sample printout from an AMPTE engineering simulator run which used the orbital elements defined in Section 5.1. In the sample run, data is generated every 15 seconds from a time well before perigee (which occurs at approximately 830901.013800)[1] to a time 22 minutes after perigee. The quantities shown are

- Spacecraft GCI position vector in kilometers
- Model geomagnetic field vector in the GCI (mG)
- Angle between the spin axis and the Sun line (degrees)

[1] Time in format YYMMDD.HHMMSS.

AMPTE ENGINEERING SIMULATOR OUTPUT HEADER RECORD

RIGHT ASCENSION OF SPIN AXIS IN GCI (DEGS).	----------	159.67227173
DECLINATION OF SPIN AXIS IN GCI(DEGS).	---------- ---	0.00000010
SATELLITE SPIN RATE(DEGS/SEC).	----------	59.99999993
ANGULAR DISPLACEMENT OF BODY FRAME FROM TRUE SPIN FRAME AT TIME=0 (DEGS).	----------	0.0
DIRECTION COSINES OF COARSE SUN SENSOR AXES IN THE BODY FRAME.	----------	0.0
	---------- ---	1.00000000
	---------- ---	0.0
DIRECTION COSINES OF MAGNETOMETER X-AXIS WITH RESPECT TO ROTATING FRAME.	---------- ---	1.00000000
	----------	0.0
	---------- ---	0.0
DIRECTION COSINES OF MAGNETOMETER Y-AXIS WITH RESPECT TO ROTATING FRAME.	----------	0.0
	----------	1.00000000
	----------	0.0
DIRECTION COSINES OF MAGNETOMETER Z-AXIS WITH RESPECT TO ROTATING FRAME.	----------	0.0
	----------	0.0
	---------- ---	1.00000000
SPIN AXIS COLATITUDE IN NOMINAL SPIN FRAME.	----------	89.99999989
SPIN AXIS AZIMUTH IN NOMINAL SPIN FRAME.	----------	89.99999989
BIAS ALONG MAGNETOMETER X-AXIS (NG).	----------	0.0
BIAS ALONG MAGNETOMETER Y-AXIS (NG).	---------- ---	0.0
BIAS ALONG MAGNETOMETER Z-AXIS (NG).	----------	0.0
MAGNETOMETER INSTRUMENTAL RESOLUTION (NG)	---------- ---	0.00000000
SUN SENSOR INSTRUMENTAL RESOLUTION (DEG)	----------	0.0
SUN SENSOR BIAS (DEG)	---------- ---	0.0

Figure 5-1. Sample AMPTE Engineering Simulator Output (1 of 2)

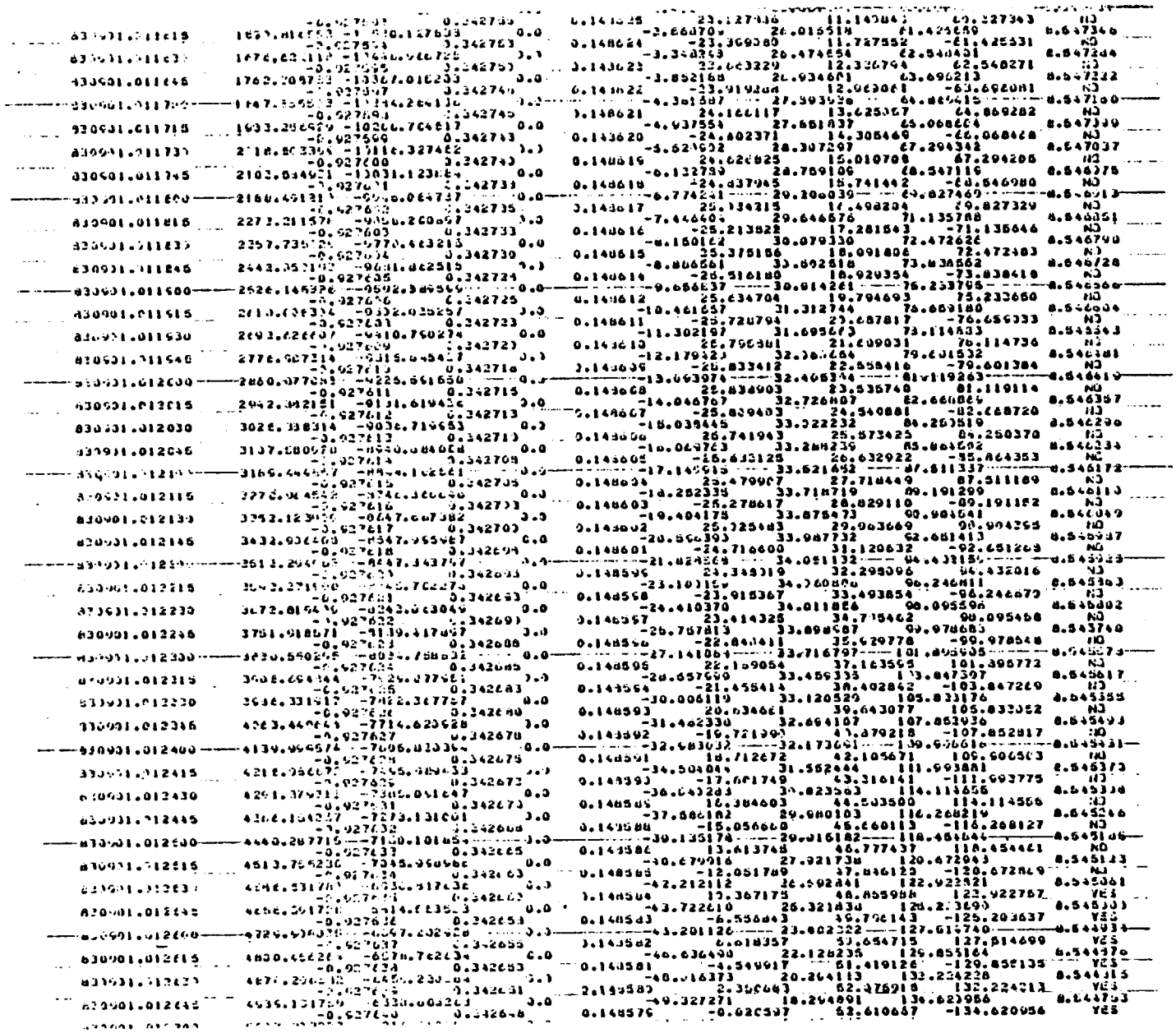

Figure 5-1. Sample AMPTE Engineering Simulator Output (2 of 2)

- Earth to Sun unit vector in the GCI
- Components of the magnetic field in the spacecraft fixed coordinate system (Reference 2)

A spin rate of 10 revolutions per minute (rpm) was assumed (Reference 3).

Figure 5-2 presents a plot of the major component of the geomagnetic field (the component that is perpendicular to the equatorial plane) against the time in minutes from perigee. The data was derived from the sample run in Figure 5-1. The magnitude of this component falls to about 50 mG (about 20 percent of perigee value) after 25 minutes from perigee. The simulator run illustrated in Figure 5-1 showed that the distribution is symmetric about perigee. The computed maximum value of the major component of the geomagnetic field at perigee is about 240 mG. The total magnitude (rms) at perigee is about 265 mG.

Work from previous missions, in particular the Solar Maximum Mission (SMM), indicates that the magnetic field should be in excess of approximately 50 mG for the magnetometers to be effective in determining spacecraft attitude. In addition, the data sample should include several variations in the strength of the field (Reference 1). In accordance with these findings, the simulator results indicate that the magnetometers may be effective only within about a 50-minute window around perigee (perigee $\pm$ 25 minutes). The effects of proximity to perigee on algorithm performance are discussed in Section 6.

5.3 EARTH OCCULTATION SIMULATION RESULTS

Given the zero-degree inclination of the CCE orbit and the relatively low altitude at perigee, the periods during which the CCE Sun sensor will be occulted by the Earth are of particular interest. The occultation algorithm in the AMPTE

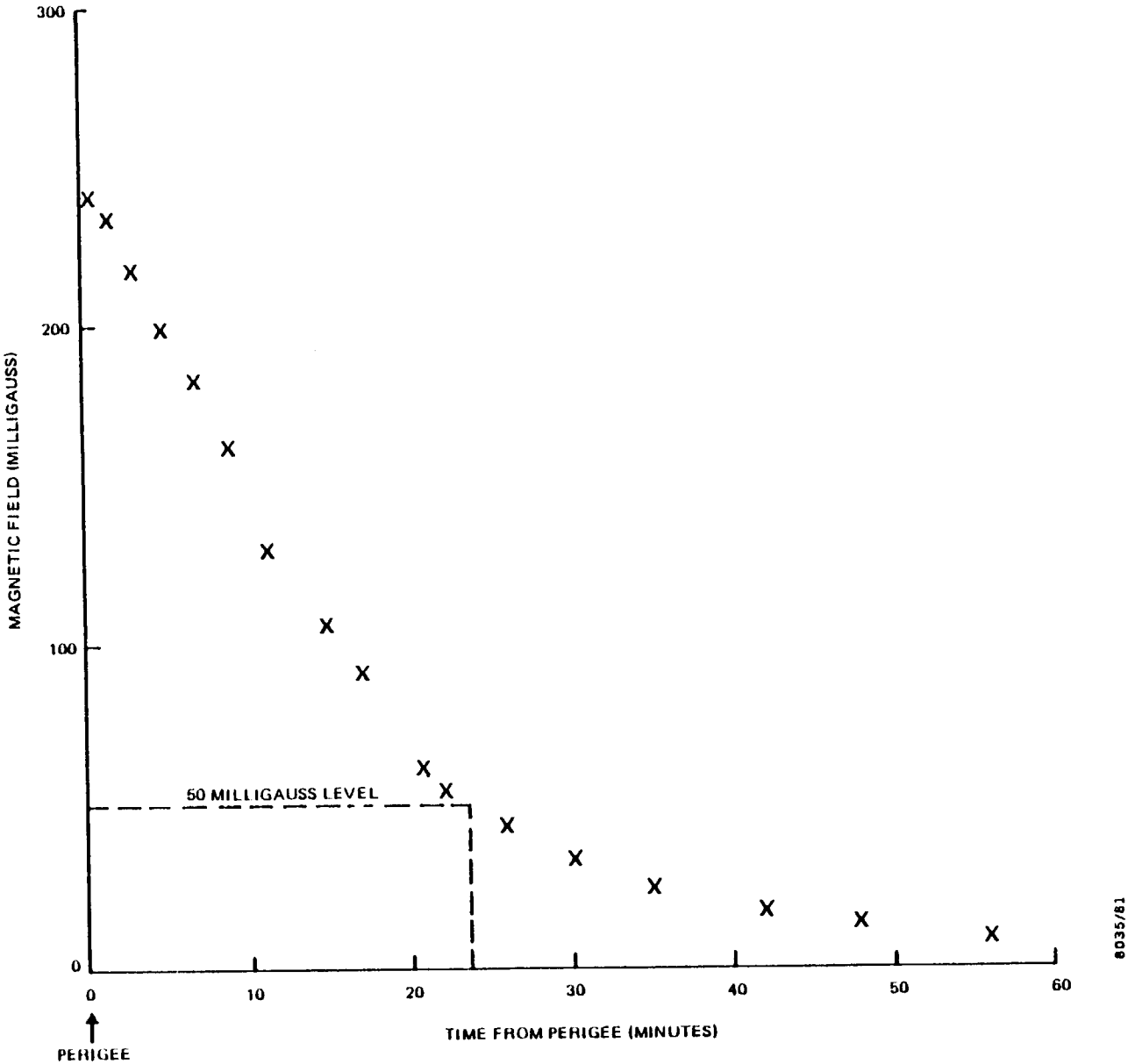

Figure 5-2. Magnitude of the Major Component of the Geomagnetic Field

engineering simulator is that of a simple cylindrical model (Reference 2). Basically, the angle between the spacecraft-to-Earth vector and a spacecraft-to-perpendicular-Earth radius vector is used as a reference. The sensor is considered occulted whenever the angle between the spacecraft-to-Earth vector and spacecraft-to-Sun vector falls below this reference. A sample result of this computation is shown in Figure 5-1; YES and NO in the right-most column indicate that the Sun is or is not occulted, respectively.

The AMPTE simulator runs indicate that the sensor will be occulted from roughly 13 minutes before perigee until 4 minutes after perigee, given that the apogee-perigee line is Sun pointing. Thus, Sun data will not be available for roughly one-third of the time during which optimal magnetometer data is available. As long as the CCE attitude remains constant, however, this may not be a problem. An essentially unlimited amount of Sun data will be available away from perigee.

SECTION 6 - TEST PROCEDURES AND RESULTS

The RESIDG and RESIDT magnetometer bias algorithms were tested to determine the variation of simulated results as a function of changes in the simulated engineering characteristics of the sensors. This section describes the tests that were run and the test results.

6.1 SOFTWARE DRIVER DEVELOPMENT

Because both RESIDG and RESIDT are in the form of FORTRAN subroutines, a driver module was developed to exercise the software. The driver routine provides for NAMELIST input that allows pertinent parameters to be varied. It also provides for the printing of results and important intermediate quantities. The subroutine that reads the AMPTE Interface Data Set (AIDS) was also included in the software package (Reference 2).

6.2 TEST OBJECTIVES

For this study, two major objectives were defined:

- First objective--To determine the performance (i.e., accuracy) of the magnetometer bias determination algorithms under varying conditions of magnetometer bias magnitude, data period, sensor granularity, orbital position (proximity to perigee), and sensor misalignment.
- Second objective--Given the test data determined by the above studies, to present specific engineering conclusions that would guide AMPTE Project engineers in selecting AMPTE hardware and software components.

6.3 MAGNETOMETER BIAS MAGNITUDE TEST RESULTS - IDEAL DATA

Several tests were made using "ideal" data to determine the effects of increasing bias magnitude on the RESIDT and

RESIDG algorithms. Ideal data is that which does not include the effects of sensor granularity. (For comparison, the tests described in the following subsections do include sensor granularity). Tables 6-1 and 6-2 show the test cases run and the test results for the tests using ideal data. Note that the biases simulated ranged from x, y, z components of 5, 10, and 15 mG up to 60, 80, and 100 mG, and that the data periods simulated were 10, 20, 30, and 60 seconds.

In the tests shown in Tables 6-1 and 6-2, the RESIDG algorithm was given the same initial bias estimate as that computed by RESIDT. The RESIDG algorithm has the capability of taking this initial estimate from NAMELIST input, whereas RESIDT cannot. These procedures were followed, however, to ensure equal testing conditions for both algorithms.

The results of the tests in Tables 6-1 and 6-2, and in succeeding tables are reported in terms of "accuracy" with accuracy defined as

$$M = \left[\sum_{i=1}^{3} (B_i - B'_i)^2 \right]^{1/2} \qquad (6\text{-}1)$$

where the B_i values are the simulated biases for the x, y, and z axes, and the B'_i values are the calculated biases.

Table 6-1 shows that the overall accuracy of the RESIDG algorithm was very good--2 mG or less for the cases in which the solution did converge. As expected, the accuracy decreased slightly with increased magnetometer bias and decreased data frequency.

At and above the biases of 40, 60, and 80 mG (which represent about 35 percent of the maximum geomagnetic field at perigee), RESIDG begins to break down. Two of the solutions diverged.

Table 6-1. Tests of Magnetometer Bias Magnitude Using RESIDG - Ideal Data

SIMULATED BIASES (MILLIGAUSS)			DATA PERIOD (SECONDS)	ITERATIONS TO CONVERGE	RESIDG RESULTS (MILLIGAUSS)						
X	Y	Z			X COMPONENT	X DEVIATION	Y COMPONENT	Y DEVIATION	Z COMPONENT	Z DEVIATION	ACCURACY
5	10	15	10	7	5.0	0.0	10.0	0.0	15.0	0.0	0.0
5	10	15	20	10	5.0	0.0	10.0	0.0	15.0	0.0	0.0
5	10	15	30	14	5.0	0.0	10.0	0.0	15.0	0.0	0.0
5	10	15	60	16	5.0	0.0	10.0	0.0	15.0	0.0	0.0
20	30	40	10	6	20.1	-0.1	30.5	-0.5	40.1	-0.1	0.52
20	30	40	20	13	20.0	0.0	30.0	0.0	40.1	-0.1	0.1
20	30	40	30	18	19.6	0.4	30.0	0.0	39.9	0.1	0.41
20	30	40	60	20	19.6	0.4	30.0	0.0	39.9	0.1	0.41
20	40	60	10	9	20.0	0.0	40.0	0.0	60.0	0.0	0.0
20	40	60	20	14	20.0	0.0	40.0	0.0	60.0	0.0	0.0
20	40	60	30	20	19.5	0.5	39.9	0.1	59.8	0.2	0.54
20	40	60	60	22	19.5	0.5	39.9	0.1	59.8	0.2	0.54
40	60	80	10	11	40.0	0.0	60.0	0.0	80.0	0.0	0.0
40	60	80	20	15	40.0	0.0	60.0	0.0	80.1	-0.1	0.1
40	60	80	30	21	38.3	1.7	59.4	0.6	79.4	0.6	1.90
40	60	80	60	23	38.2	1.8	59.5	0.5	79.5	0.5	1.93
60	80	40	10	*	--	--	--	--	--	--	--
80	40	60	10	11	80.0	0.0	40.0	0.0	60.0	0.0	0.0
60	80	100	10	*	--	--	--	--	--	--	--

*DIVERGED

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Table 6-2. Tests of Magnetometer Bias Magnitude Using RESIDT - Ideal Data

SIMULATED BIASES (MILLIGAUSS)			DATA PERIOD (SECONDS)	ITERATIONS TO CONVERGE	RESIDT RESULTS (MILLIGAUSS)						
X	Y	Z			X COMPONENT	X DEVIATION	Y COMPONENT	Y DEVIATION	Z COMPONENT	Z DEVIATION	ACCURACY
5	10	15	10	7	5.0	0.0	10.0	0.0	15.0	0.0	0.0
5	10	15	20	4	5.0	0.0	10.0	0.0	15.0	0.0	0.0
5	10	15	30	19	4.98	0.02	9.99	0.01	15.0	0.0	0.02
5	10	15	60	19	5.0	0.0	10.0	0.0	15.0	0.0	0.0
20	30	40	10	5	20.0	0.0	30.0	0.0	40.0	0.0	0.0
20	30	40	20	10	20.0	0.0	30.0	0.0	40.0	0.0	0.0
20	30	40	30	43	19.9	0.1	29.8	0.2	40.0	0.0	0.22
20	30	40	60	46	19.8	0.2	29.8	0.2	40.0	0.0	0.28
20	40	60	10	7	20.0	0.0	40.0	0.0	60.0	0.0	0.0
20	40	60	20	17	20.0	0.0	39.9	0.1	60.0	0.0	0.1
20	40	60	30	58	19.7	0.3	39.6	0.4	60.0	0.0	0.50
20	40	60	60	61	19.6	0.4	39.6	0.4	59.9	0.1	0.57
40	60	80	10	15	40.0	0.0	59.9	0.1	80.0	0.0	0.1
40	60	80	20	29	40.0	0.0	59.7	0.3	79.9	0.1	0.32
40	60	80	30	74	38.9	0.1	58.8	1.2	79.8	0.2	1.22
40	60	80	60	78	38.8	0.2	58.6	1.4	79.8	0.2	1.43
60	80	40	10	17	60.0	0.0	79.9	0.1	40.0	0.0	0.1
80	40	60	10	14	80.0	0.0	40.0	0.0	60.0	0.0	0.0
60	80	100	10	16	60.0	0.0	79.8	0.2	100.0	0.0	0.2

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Table 6-2 shows that the overall accuracy of the RESIDT algorithm, like the RESIDG algorithm, is very good under ideal conditions. The overall errors ranged from zero to about 1-1/2 mG. As was the case in Table 6-1, the RESIDT algorithm shows that accuracy decreased slightly with increasing magnetometer bias magnitude and decreasing data frequency. However, one significant attribute of the RESIDT algorithm was that it did converge for all the test cases, whereas the RESIDG algorithm diverged for two of the test cases.

More extensively detailed and realistic (granularity included) tests are described in Section 6.4.

6.4 DATA PERIOD AND SENSOR GRANULARITY TEST RESULTS

Tests for the combined effects of data frequency and sensor granularity were conducted for both the RESIDG and RESIDT algorithms. For RESIDG, the tests used the initial bias estimates from the RESIDG initial estimator. As stated previously, RESIDT generates its own initial estimate of the biases.

Tables 6-3 and 6-4 show the tests that were run using the RESIDG and RESIDT algorithms, respectively. The left-hand columns show that magnetometer biases of x, y, z component values of 5, 10, 15 and 40, 60, 80 mG were simulated. For each combination of magnetometer bias, sensor granularities of 1.6 mG, 3.2 mG, 5.0 mG, 8.0 mG, and 14.0 mG were simulated. With each combination of bias magnitude and sensor granularity, solutions were obtained for data periods ranging from 6 seconds to 42 seconds in increments of 2 seconds.

The right-hand columns in Tables 6-3 and 6-4 show the computed magnetometer bias for each (x, y, z) component, and the deviation of the computed bias from the simulated bias.

Table 6-3. RESIDG Data Period and Sensor Granularity Test Results (1 of 3)

RESIDG RESULTS FOR 2 SEC. BASE RATE

SIMULATED BIASES X	Y	Z	GRANU-LARITY	DATA PERIOD (SECS)	ITERATIONS TO CONVERGE	X-COMP BIAS DEVIATION (MG)	(MG)	Y-COMP BIAS DEVIATION (MG)	(MG)	Z-COMP BIAS DEVIATION (MG)	(MG)	TOTAL DEVIATION
5.0	10.0	15.0	1.6	6	2	4.899	-0.1012	10.728	0.7285	15.290	0.2897	0.7905
5.0	10.0	15.0	1.6	8	5	5.013	0.0131	10.149	0.1488	14.960	-0.0398	0.1546
5.0	10.0	15.0	1.6	10	1	5.134	0.1337	9.946	-0.0537	15.086	0.0861	0.1678
5.0	10.0	15.0	1.6	12	4	4.349	-0.6522	11.511	1.5107	15.648	0.6482	1.7606
5.0	10.0	15.0	1.6	14	2	5.020	0.0202	10.050	0.0501	14.965	-0.0353	0.0665
5.0	10.0	15.0	1.6	16	2	5.131	0.1314	10.300	0.2998	14.983	-0.0173	0.3278
5.0	10.0	15.0	1.6	18	2	4.840	-0.1601	10.635	0.6349	15.190	0.1899	0.6818
5.0	10.0	15.0	1.6	20	2	5.151	0.1508	10.094	0.0943	15.156	0.1561	0.2367
5.0	10.0	15.0	1.6	22	1	5.106	0.1058	10.105	0.1052	15.049	0.0488	0.1570
5.0	10.0	15.0	1.6	24	5	4.736	-0.2636	11.076	1.0759	15.363	0.3631	1.1657
5.0	10.0	15.0	1.6	26	3	5.070	0.0704	10.000	0.0	15.060	0.0595	0.0922
5.0	10.0	15.0	1.6	28	3	5.027	0.0269	10.167	0.1665	14.958	-0.0416	0.1737
5.0	10.0	15.0	1.6	30	1	4.960	-0.0400	10.280	0.2795	15.225	0.2250	0.3611
5.0	10.0	15.0	1.6	32	2	5.237	0.2366	10.348	0.3482	15.036	0.0958	0.4318
5.0	10.0	15.0	1.6	34	1	4.879	-0.1215	9.505	-0.4946	15.025	0.0253	0.5059
5.0	10.0	15.0	1.6	36	5	4.153	-0.8475	12.018	2.0185	15.826	0.8260	2.3398
5.0	10.0	15.0	1.6	38	3	5.197	0.1971	9.939	-0.0610	15.126	0.1262	0.2419
5.0	10.0	15.0	1.6	40	3	5.039	0.0391	10.214	0.2136	15.060	0.0604	0.2254
5.0	10.0	15.0	1.6	42	3	4.751	-0.2490	11.397	1.3971	15.492	0.4916	1.5019
5.0	10.0	15.0	3.2	6	4	5.295	0.2946	8.548	-1.4521	14.506	-0.4943	1.5620
5.0	10.0	15.0	3.2	8	1	5.158	0.1577	9.700	-0.3001	15.005	0.0049	0.3391
5.0	10.0	15.0	3.2	10	2	5.009	0.0093	10.093	0.0926	14.885	-0.1152	0.1481
5.0	10.0	15.0	3.2	12	4	5.707	0.7069	8.636	-1.3637	14.389	-0.6113	1.6532
5.0	10.0	15.0	3.2	14	2	4.871	-0.1292	9.044	-0.9558	15.301	0.3015	1.0105
5.0	10.0	15.0	3.2	16	3	5.090	0.0895	9.330	-0.6696	15.087	0.0870	0.6811
5.0	10.0	15.0	3.2	18	5	5.111	0.1110	11.707	1.7072	15.823	0.8230	1.8985
5.0	10.0	15.0	3.2	20	1	4.840	-0.1601	9.922	-0.0781	14.821	-0.1794	0.2528
5.0	10.0	15.0	3.2	22	3	5.418	0.4181	9.082	-0.9180	14.989	-0.0112	1.0088
5.0	10.0	15.0	3.2	24	1	4.256	-0.7439	9.794	-0.2056	15.132	0.1324	0.7830
5.0	10.0	15.0	3.2	26	1	4.974	-0.0263	9.534	-0.4661	14.605	-0.3953	0.6118
5.0	10.0	15.0	3.2	28	1	4.804	-0.1962	9.079	-0.9208	15.410	0.4100	1.0269
5.0	10.0	15.0	3.2	30	6	6.457	1.4574	9.694	-0.3061	14.598	-0.4017	1.5424
5.0	10.0	15.0	3.2	32	3	5.195	0.1950	8.940	-1.0599	14.870	-0.1300	1.0855
5.0	10.0	15.0	3.2	34	4	4.861	-0.1386	10.643	0.6430	14.960	-0.0401	0.6590
5.0	10.0	15.0	3.2	36	6	5.222	0.2218	11.649	1.6485	15.635	0.6350	1.7805
5.0	10.0	15.0	3.2	38	4	5.059	0.0592	9.776	-0.2239	15.098	0.0979	0.2514
5.0	10.0	15.0	3.2	40	1	5.073	0.0730	10.144	0.1440	14.749	-0.2514	0.2988
5.0	10.0	15.0	3.2	42	4	4.209	-0.7909	6.826	-3.1743	14.615	-0.3846	3.2939
5.0	10.0	15.0	5.0	6	6	4.797	-0.2032	9.908	-0.0920	15.183	0.1830	0.2885
5.0	10.0	15.0	5.0	8	1	5.126	0.1262	9.628	-0.3719	15.232	0.2316	0.4559
5.0	10.0	15.0	5.0	10	3	4.512	-0.4877	9.756	-0.2436	15.079	0.0794	0.5509
5.0	10.0	15.0	5.0	12	6	4.028	-0.9720	9.536	-0.4644	15.244	0.2440	1.1045
5.0	10.0	15.0	5.0	14	2	5.019	0.0192	8.627	-1.3726	15.066	0.0658	1.3743
5.0	10.0	15.0	5.0	16	1	5.128	0.1280	10.146	0.1457	15.582	0.5824	0.6139
5.0	10.0	15.0	5.0	18	7	4.050	-0.9496	9.088	-0.9121	15.166	0.1657	1.3271
5.0	10.0	15.0	5.0	20	3	4.460	-0.5396	10.233	-0.2332	15.174	0.1749	0.6130
5.0	10.0	15.0	5.0	22	2	6.288	0.2879	8.880	-1.1202	14.945	-0.0553	1.1580
5.0	10.0	15.0	5.0	24	6	3.190	-1.8097	10.414	0.4137	15.787	0.7870	2.0143
5.0	10.0	15.0	5.0	26	3	4.834	-0.1664	10.034	0.0341	14.948	-0.0517	0.1776
5.0	10.0	15.0	5.0	28	2	5.038	0.0382	8.616	-1.3840	15.198	0.1976	1.3985
5.0	10.0	15.0	5.0	30	7	2.841	-2.1593	10.567	0.5670	15.562	0.5619	2.3022
5.0	10.0	15.0	5.0	32	3	5.517	0.5170	10.954	0.9536	15.878	0.8779	1.3955
5.0	10.0	15.0	5.0	34	4	5.248	0.2481	8.330	-1.6700	15.057	0.0566	1.6893
5.0	10.0	15.0	5.0	36	4	2.567	-2.4331	8.870	-1.1303	15.535	0.5354	2.7358
5.0	10.0	15.0	5.0	38	4	5.418	0.4179	8.807	-1.1929	14.126	-0.8744	1.5369
5.0	10.0	15.0	5.0	40	4	4.665	-0.3448	11.006	1.0058	15.277	0.2771	1.0463
5.0	10.0	15.0	5.0	42	9	3.261	-1.7391	8.655	-1.3447	15.297	0.2965	2.2142
5.0	10.0	15.0	8.0	6	7	6.280	1.2803	5.211	-4.7894	13.760	-1.2400	5.1103
5.0	10.0	15.0	8.0	8	3	5.142	0.1422	9.811	-0.1892	15.449	0.4486	0.5072
5.0	10.0	15.0	8.0	10	1	5.359	0.3589	9.107	-0.8931	15.493	0.4931	1.0815
5.0	10.0	15.0	8.0	12	7	5.972	0.9725	6.545	-3.4550	14.235	-0.7651	3.6659
5.0	10.0	15.0	8.0	14	3	4.654	-0.3459	9.113	-0.8870	14.896	-0.1037	0.9577
5.0	10.0	15.0	8.0	16	8	5.672	0.6720	8.839	-1.1611	15.563	0.5631	1.4549
5.0	10.0	15.0	8.0	18	4	6.888	1.8875	3.309	-6.6914	12.860	-2.1397	7.2743
5.0	10.0	15.0	8.0	20	3	5.396	0.3958	8.650	-1.3500	15.167	0.1668	1.4167
5.0	10.0	15.0	8.0	22	7	5.370	0.3704	9.493	-0.5069	15.965	0.9655	1.1517
5.0	10.0	15.0	8.0	24	4	4.831	-0.1695	9.884	-0.1155	15.616	0.6164	0.6496
5.0	10.0	15.0	8.0	26	3	5.323	0.3228	11.189	1.1888	15.059	0.0593	1.2333
5.0	10.0	15.0	8.0	28	4	4.790	-0.2098	8.221	-1.7790	14.793	-0.2072	1.8033
5.0	10.0	15.0	8.0	30	1	6.218	1.2179	7.457	-2.5430	14.859	-0.1411	2.8231
5.0	10.0	15.0	8.0	32	1	6.335	1.3354	9.002	-0.9981	16.092	1.0921	1.5930
5.0	10.0	15.0	8.0	34	4	5.085	0.0850	8.718	-1.2825	15.879	0.8788	1.5570
5.0	10.0	15.0	8.0	36	9	5.161	0.1614	6.833	-3.1669	14.348	-0.6523	3.2374
5.0	10.0	15.0	8.0	38	2	5.586	0.5856	9.782	-0.2164	16.104	1.1043	1.2609
5.0	10.0	15.0	8.0	40	4	4.390	-0.6100	8.092	-1.9080	14.814	-0.1859	2.0118
5.0	10.0	15.0	8.0	42	12	3.538	-1.4616	0.658	-9.3419	12.186	-2.8144	9.8655

Table 6-3. RESIDG Data Period and Sensor Granularity Test Results (2 of 3)

RESIDG RESULTS FOR 2 SEC. BASE RATE

SIMULATED BIASES X	Y	Z	GRANU-LARITY	DATA PERIOD (SECS)	ITERATIONS TO CONVERGE	X-COMP BIAS (MG)	X-COMP DEVIATION (MG)	Y-COMP BIAS (MG)	Y-COMP DEVIATION (MG)	Z-COMP BIAS (MG)	Z-COMP DEVIATION (MG)	TOTAL DEVIATION
5.0	10.0	15.0	14.0	6	9	2.323	-2.6767	15.576	5.5762	17.039	2.0386	6.5126
5.0	10.0	15.0	14.0	8	3	4.258	-0.7419	10.198	0.1977	14.951	-0.0494	0.7694
5.0	10.0	15.0	14.0	10	4	4.459	-0.5414	10.435	0.4346	14.902	-0.0975	0.7010
5.0	10.0	15.0	14.0	12	9	1.068	-3.9321	16.960	6.9603	17.794	2.7936	8.4683
5.0	10.0	15.0	14.0	14	4	3.933	-1.0665	11.166	1.1664	15.420	0.4200	1.6353
5.0	10.0	15.0	14.0	16	2	3.290	-1.7103	10.949	0.9490	15.127	0.1275	1.9601
5.0	10.0	15.0	14.0	18	9	2.027	-2.9733	13.526	3.5258	16.304	1.3037	4.7929
5.0	10.0	15.0	14.0	20	4	3.864	-1.1362	10.389	0.3887	14.963	-0.0370	1.2014
5.0	10.0	15.0	14.0	22	3	4.447	-0.5525	8.782	-1.2182	14.512	-0.4885	1.4241
5.0	10.0	15.0	14.0	24	11	0.069	-4.9315	12.701	2.7012	16.448	1.4485	5.8064
5.0	10.0	15.0	14.0	26	3	5.127	-0.1268	10.497	0.8972	15.452	0.4520	1.0126
5.0	10.0	15.0	14.0	28	4	3.494	-1.5057	13.311	3.3106	15.568	0.5677	3.6810
5.0	10.0	15.0	14.0	30	10	3.420	-1.5801	25.174	15.1739	21.015	6.0145	16.3987
5.0	10.0	15.0	14.0	32	5	2.171	-2.8288	9.039	-0.9611	16.288	1.2880	3.2534
5.0	10.0	15.0	14.0	34	6	5.776	0.7756	7.616	-2.3836	15.549	0.5428	2.5647
5.0	10.0	15.0	14.0	36	14	-0.279	-5.2792	16.802	6.8018	18.501	3.5014	9.2949
5.0	10.0	15.0	14.0	38	3	4.222	-0.7779	10.773	0.7726	16.039	1.0390	1.5105
5.0	10.0	15.0	14.0	40	4	2.505	-2.4945	10.130	0.1297	15.944	0.9442	2.6704
5.0	10.0	15.0	14.0	42	8	-0.811	-5.8109	28.740	18.7402	23.197	8.1975	21.2640
40.0	60.0	80.0	1.6	6	1	40.270	0.2701	59.109	-0.8907	79.485	-0.5151	1.0638
40.0	60.0	80.0	1.6	8	1	40.015	0.0153	59.427	-0.5729	79.991	-0.0088	0.5732
40.0	60.0	80.0	1.6	10	1	39.936	-0.0637	59.919	-0.0812	79.976	-0.0239	0.1060
40.0	60.0	80.0	1.6	12	1	41.111	1.1108	57.940	-2.0602	78.865	-1.1347	2.6011
40.0	60.0	80.0	1.6	14	1	39.970	-0.0303	59.016	-0.9836	80.122	0.1221	0.9916
40.0	60.0	80.0	1.6	16	1	40.156	0.1562	59.873	-0.1266	79.955	-0.0455	0.2061
40.0	60.0	80.0	1.6	18	1	39.760	-0.2401	59.693	-0.3069	79.500	-0.5002	0.6341
40.0	60.0	80.0	1.6	20	1	40.012	0.0123	59.876	-0.1238	79.907	-0.0928	0.1553
40.0	60.0	80.0	1.6	22	1	40.060	0.0599	60.344	0.3437	79.990	-0.0102	0.3490
40.0	60.0	80.0	1.6	24	1	40.977	0.9774	57.892	-2.1078	79.019	-0.9812	2.5221
40.0	60.0	80.0	1.6	26	1	40.067	0.0674	59.907	-0.0932	80.017	0.0165	0.1162
40.0	60.0	80.0	1.6	28	1	40.079	0.0785	58.602	-1.3983	80.027	0.0266	1.4007
40.0	60.0	80.0	1.6	30	2	40.069	0.0694	59.057	-0.9433	78.843	-1.1568	1.4942
40.0	60.0	80.0	1.6	32	1	40.081	0.0812	58.729	-1.2713	79.865	-0.1351	1.2811
40.0	60.0	80.0	1.6	34	2	40.007	0.0071	58.846	-1.1545	79.876	-0.1239	1.1611
40.0	60.0	80.0	1.6	36	1	40.624	0.6239	58.637	-1.3625	78.886	-1.1142	1.8674
40.0	60.0	80.0	1.6	38	1	39.931	-0.0690	61.726	1.7258	79.662	-0.1383	1.7327
40.0	60.0	80.0	1.6	40	1	39.876	-0.1242	60.227	0.2274	80.008	-0.0917	0.2748
40.0	60.0	80.0	1.6	42	1	41.071	1.0712	58.761	-1.2390	79.611	-0.3886	1.6833
40.0	60.0	80.0	3.2	6	1	40.156	0.1561	59.727	-0.2727	79.915	-0.0846	0.3294
40.0	60.0	80.0	3.2	8	1	39.989	-0.0113	60.361	0.3614	79.995	-0.0052	0.3616
40.0	60.0	80.0	3.2	10	2	39.979	-0.0213	58.102	-1.8976	79.925	-0.0747	1.8992
40.0	60.0	80.0	3.2	12	1	39.165	-0.8353	62.034	2.0343	81.330	1.3304	2.5702
40.0	60.0	80.0	3.2	14	1	39.901	-0.0994	60.073	0.0726	80.022	0.0219	0.1250
40.0	60.0	80.0	3.2	16	1	40.017	0.0170	59.793	-0.2074	79.846	-0.1535	0.2586
40.0	60.0	80.0	3.2	18	1	40.590	0.5900	59.388	-0.6124	79.862	-0.1385	0.8616
40.0	60.0	80.0	3.2	20	2	39.871	-0.1292	58.076	-1.9238	79.917	-0.0826	1.9299
40.0	60.0	80.0	3.2	22	5	40.288	0.2876	61.459	1.4586	80.131	0.1311	1.4025
40.0	60.0	80.0	3.2	24	2	39.884	-0.1164	58.837	-1.1634	78.498	-1.3024	1.7503
40.0	60.0	80.0	3.2	26	1	40.261	0.2607	59.430	-0.5705	80.022	0.0218	0.6276
40.0	60.0	80.0	3.2	28	2	39.899	-0.1007	58.419	-1.5809	79.872	-0.1284	1.5893
40.0	60.0	80.0	3.2	30	1	39.854	-0.1456	57.378	-2.6222	78.443	-1.5567	3.0529
40.0	60.0	80.0	3.2	32	1	39.783	-0.2172	59.093	-0.9072	79.890	-0.1098	0.9303
40.0	60.0	80.0	3.2	34	5	40.191	0.1909	59.050	-0.9496	80.179	0.1789	0.9850
40.0	60.0	80.0	3.2	36	2	40.519	0.5194	62.193	2.1926	81.594	1.5936	2.7599
40.0	60.0	80.0	3.2	38	3	40.174	0.1745	60.173	0.1727	79.550	-0.4505	0.5130
40.0	60.0	80.0	3.2	40	1	39.941	-0.0592	60.125	0.1254	79.882	-0.1175	0.1817
40.0	60.0	80.0	3.2	42	1	39.014	-0.9864	58.404	-1.1958	78.979	-1.0205	1.8559
40.0	60.0	80.0	5.0	6	1	39.814	-0.1863	61.588	1.5880	81.818	1.8176	2.4208
40.0	60.0	80.0	5.0	8	1	40.125	0.1246	59.132	-0.8677	80.231	0.2315	0.9066
40.0	60.0	80.0	5.0	10	2	39.511	-0.4892	60.998	0.9980	80.075	0.0746	1.1140
40.0	60.0	80.0	5.0	12	1	39.048	-0.9521	60.896	0.8963	81.571	1.5705	2.0436
40.0	60.0	80.0	5.0	14	1	40.022	0.0223	59.815	-0.1853	80.063	0.0628	0.1969
40.0	60.0	80.0	5.0	16	1	40.129	0.1293	59.812	-0.1884	80.582	0.5819	0.6251
40.0	60.0	80.0	5.0	18	4	39.080	-0.9196	60.685	0.6847	81.730	1.7247	2.0752
40.0	60.0	80.0	5.0	20	3	39.452	-0.5476	58.938	-1.0615	80.179	0.1787	1.2077
40.0	60.0	80.0	5.0	22	2	40.288	0.2882	59.945	-0.0547	79.942	-0.0578	0.2880
40.0	60.0	80.0	5.0	24	2	38.229	-1.7708	61.959	1.9589	82.291	2.2906	3.4957
40.0	60.0	80.0	5.0	26	5	39.834	-0.1656	58.784	-1.2158	79.946	-0.0537	1.2282
40.0	60.0	80.0	5.0	28	5	40.036	0.0364	57.356	-2.6444	80.199	0.1917	2.6521
40.0	60.0	80.0	5.0	30	7	37.782	-2.2183	59.324	-0.6759	79.279	-0.7211	2.4285
40.0	60.0	80.0	5.0	32	4	40.521	0.5214	59.698	-0.3020	80.883	0.8833	1.0692
40.0	60.0	80.0	5.0	34	5	40.256	0.2562	57.389	-2.6105	80.058	0.0581	2.6237
40.0	60.0	80.0	5.0	36	4	37.614	-2.3057	60.250	0.2503	81.873	1.8728	3.0433
40.0	60.0	80.0	5.0	38	6	40.405	0.4049	57.808	-2.1916	79.136	-0.8637	2.3902
40.0	60.0	80.0	5.0	40	6	39.658	-0.3423	62.199	2.1994	80.259	0.2594	2.2409
40.0	60.0	80.0	5.0	42	7	38.303	-1.6965	60.079	0.0794	81.664	1.6641	2.3778

Table 6-3. RESIDG Data Period and Sensor Granularity Test Results (3 of 3)

RESIDG RESULTS FOR 2 SEC. BASE RATE

SIMULATED BIASES X	Y	Z	GRANU-LARITY	DATA PERIOD (SECS)	ITERATIONS TO CONVERGE	X-COMP BIAS (MG)	X-COMP DEVIATION (MG)	Y-COMP BIAS (MG)	Y-COMP DEVIATION (MG)	Z-COMP BIAS (MG)	Z-COMP DEVIATION (MG)	TOTAL DEVIATION
40.0	60.0	80.0	8.0	6	3	40.011	0.0105	61.009	1.0092	81.300	1.2997	1.6456
40.0	60.0	80.0	8.0	8	2	39.644	-0.3560	61.288	1.2884	79.930	-0.0698	1.3385
40.0	60.0	80.0	8.0	10	1	39.979	-0.0206	60.047	0.0466	80.096	0.0957	0.1084
40.0	60.0	80.0	8.0	12	3	40.800	0.7999	59.574	-0.4256	80.428	0.4281	1.0021
40.0	60.0	80.0	8.0	14	16	40.207	0.2074	59.703	-0.2970	79.866	-0.1344	0.3864
40.0	60.0	80.0	8.0	16	1	39.754	-0.2461	59.887	-0.1131	80.525	0.5245	0.5903
40.0	60.0	80.0	8.0	18	4	40.008	0.0078	61.137	1.1366	81.267	1.2673	1.7024
40.0	60.0	80.0	8.0	20	1	40.206	0.2061	62.980	2.9801	79.743	-0.2566	2.9983
40.0	60.0	80.0	8.0	22	7	39.542	-0.4584	62.285	2.2845	79.615	-0.3852	2.3617
40.0	60.0	80.0	8.0	24	1	41.042	1.0424	59.858	-0.1418	80.831	0.8307	1.3405
40.0	60.0	80.0	8.0	26	3	39.814	-0.1862	61.690	1.6901	79.920	-0.0796	1.7022
40.0	60.0	80.0	8.0	28	23	40.066	0.0661	61.724	1.7240	80.361	0.3614	1.7627
40.0	60.0	80.0	8.0	30	1	40.436	0.4362	61.538	1.5376	81.027	1.0268	1.8997
40.0	60.0	80.0	8.0	32	8	39.588	-0.4117	63.187	3.1867	80.647	0.6465	3.2776
40.0	60.0	80.0	8.0	34	1	39.227	-0.7730	62.225	2.2250	80.637	0.6373	2.4401
40.0	60.0	80.0	8.0	36	3	43.409	3.4091	56.964	-3.0355	79.131	-0.8686	4.6466
40.0	60.0	80.0	8.0	38	3	40.391	0.3912	62.955	2.9549	80.313	0.3134	2.9971
40.0	60.0	80.0	8.0	40	4	39.657	-0.3427	61.047	1.0471	79.020	-0.9798	1.4744
40.0	60.0	80.0	8.0	42	7	40.301	0.3014	48.014	-11.9864	74.860	-5.1400	13.0455
40.0	60.0	80.0	14.0	6	5	43.207	3.2072	50.425	-9.5746	78.296	-1.7043	10.2403
40.0	60.0	80.0	14.0	8	3	40.285	0.2845	60.121	0.1212	80.778	0.7778	0.8371
40.0	60.0	80.0	14.0	10	3	40.102	0.1021	59.404	-0.5960	80.492	0.4919	0.7795
40.0	60.0	80.0	14.0	12	7	42.937	2.9371	52.798	-7.2020	79.272	-0.7277	7.8119
40.0	60.0	80.0	14.0	14	1	38.874	-1.1257	59.156	-0.8441	80.096	0.0963	1.4103
40.0	60.0	80.0	14.0	16	6	40.924	0.9236	57.068	-2.9323	80.624	0.6241	3.1371
40.0	60.0	80.0	14.0	18	4	44.238	4.2376	48.921	-11.0792	77.698	-2.3015	12.0832
40.0	60.0	80.0	14.0	20	2	39.304	-0.6956	54.942	-5.0580	79.220	-0.7796	5.1647
40.0	60.0	80.0	14.0	22	13	41.366	1.3665	63.423	3.4232	81.374	1.3740	3.9337
40.0	60.0	80.0	14.0	24	4	42.067	2.0670	48.803	-11.1970	78.233	-1.7675	11.5226
40.0	60.0	80.0	14.0	26	4	39.025	-0.9746	55.215	-4.7847	80.440	0.4402	4.9028
40.0	60.0	80.0	14.0	28	7	40.452	0.4522	58.687	-1.3132	79.787	-0.2128	1.4051
40.0	60.0	80.0	14.0	30	5	43.356	3.3558	51.087	-8.9126	78.668	-1.3325	9.6162
40.0	60.0	80.0	14.0	32	6	40.988	0.9882	61.139	1.1393	79.929	-0.0714	1.5099
40.0	60.0	80.0	14.0	34	9	38.026	-1.9743	60.331	0.3313	79.683	-0.3167	2.0268
40.0	60.0	80.0	14.0	36	1	42.822	2.8218	42.670	-17.3207	75.638	-4.3623	18.0831
40.0	60.0	80.0	14.0	38	6	40.483	0.4834	57.078	-2.9216	79.677	-0.3230	2.9789
40.0	60.0	80.0	14.0	40	5	40.044	0.0439	56.819	-3.1814	79.558	-0.4422	3.2123
40.0	60.0	80.0	14.0	42	3	45.250	5.2502	48.739	-11.2612	77.147	-2.8534	12.7483

Table 6-4. RESIDT Data Period and Sensor Granularity Test Results (1 of 3)

SIMULATED BIASES X	SIMULATED BIASES Y	SIMULATED BIASES Z	GRANULARITY	DATA PERIOD (SECS)	ITERATIONS TO CONVERGE	X-COMP BIAS (MG)	X DEVIATION (MG)	Y-COMP BIAS (MG)	Y DEVIATION (MG)	Z-COMP BIAS (MG)	Z DEVIATION (MG)	TOTAL DEVIATION
5.0	10.0	15.0	1.6	6	55	4.943	-0.0567	10.559	0.5595	15.194	0.1937	0.5948
5.0	10.0	15.0	1.6	8	12	5.013	0.0130	10.173	0.1729	14.960	-0.0401	0.1760
5.0	10.0	15.0	1.6	10	11	5.134	0.1338	9.977	-0.0231	15.086	0.0864	0.1609
5.0	10.0	15.0	1.6	12	55	4.395	-0.6048	11.336	1.3363	15.554	0.5540	[illegible]
5.0	10.0	15.0	1.6	14	12	5.020	0.0203	10.082	0.0821	14.964	-0.0357	[illegible]
5.0	10.0	15.0	1.6	16	12	5.131	0.1312	10.315	0.3155	14.982	-0.0176	0.3421
5.0	10.0	15.0	1.6	18	54	4.881	-0.1194	10.465	0.4651	15.091	0.0910	[illegible]
5.0	10.0	15.0	1.6	20	12	5.151	0.1509	10.124	0.1237	15.156	0.1558	[illegible]
5.0	10.0	15.0	1.6	22	13	5.106	0.1058	10.115	0.1154	15.049	[illegible]	[illegible]
5.0	10.0	15.0	1.6	24	53	4.778	-0.2223	10.901	0.9015	15.265	0.2651	[illegible]
5.0	10.0	15.0	1.6	26	12	5.070	0.0703	9.979	-0.0207	15.059	0.0592	0.0942
5.0	10.0	15.0	1.6	28	12	5.027	0.0270	10.193	0.1934	14.958	-0.0418	[illegible]
5.0	10.0	15.0	1.6	30	52	4.996	-0.0040	10.166	0.1662	15.178	0.1778	[illegible]
5.0	10.0	15.0	1.6	32	12	5.236	0.2365	10.371	0.3713	15.095	0.0953	[illegible]
5.0	10.0	15.0	1.6	34	10	4.878	-0.1218	9.530	-0.4704	15.025	0.0248	[illegible]
5.0	10.0	15.0	1.6	36	53	4.195	-0.8050	11.843	1.8429	15.732	0.7318	[illegible]
5.0	10.0	15.0	1.6	38	11	5.197	0.1975	9.961	-0.0389	15.126	0.1265	0.2377
5.0	10.0	15.0	1.6	40	11	5.039	0.0393	10.233	0.2330	15.060	[illegible]	[illegible]
5.0	10.0	15.0	1.6	42	52	4.786	-0.2142	11.236	1.2361	15.402	[illegible]	[illegible]
5.0	10.0	15.0	1.6	44	12	5.143	0.1431	10.187	0.1867	15.260	[illegible]	[illegible]
5.0	10.0	15.0	1.6	46	11	5.114	0.1143	10.547	0.5470	14.923	-0.0771	[illegible]
5.0	10.0	15.0	3.2	6	53	5.331	0.3310	8.485	-1.5146	14.499	[illegible]	[illegible]
5.0	10.0	15.0	3.2	8	11	5.158	0.1578	9.690	-0.3095	15.005	[illegible]	[illegible]
5.0	10.0	15.0	3.2	10	12	5.009	0.0092	10.101	0.1012	14.985	-0.1154	[illegible]
5.0	10.0	15.0	3.2	12	52	5.741	0.7415	8.580	-1.4197	14.388	-0.6121	[illegible]
5.0	10.0	15.0	3.2	14	10	4.871	-0.1294	9.028	-0.9719	15.301	0.3012	[illegible]
5.0	10.0	15.0	3.2	16	10	5.089	0.0895	9.307	-0.6930	15.087	0.0867	[illegible]
5.0	10.0	15.0	3.2	18	54	5.160	0.1604	11.602	1.6019	15.501	[illegible]	[illegible]
5.0	10.0	15.0	3.2	20	11	4.840	-0.1602	9.892	-0.1075	14.821	-0.1793	[illegible]
5.0	10.0	15.0	3.2	22	10	5.418	0.4180	9.064	-0.9261	14.988	-0.6115	[illegible]
5.0	10.0	15.0	3.2	24	52	4.294	-0.7057	9.692	-0.3076	[illegible]	[illegible]	[illegible]
5.0	10.0	15.0	3.2	26	11	4.974	-0.0262	9.535	-0.4652	14.605	[illegible]	[illegible]
5.0	10.0	15.0	3.2	28	10	4.804	-0.1963	9.060	-0.9397	15.410	[illegible]	[illegible]
5.0	10.0	15.0	3.2	30	50	6.491	1.4912	9.547	-0.4532	14.516	[illegible]	[illegible]
5.0	10.0	15.0	3.2	32	10	5.195	0.1950	8.924	-1.0762	14.970	-0.1300	[illegible]
5.0	10.0	15.0	3.2	34	12	4.861	-0.1389	10.661	0.6609	14.960	[illegible]	[illegible]
5.0	10.0	15.0	3.2	36	51	5.264	0.2642	11.559	1.5590	[illegible]	0.6216	[illegible]
5.0	10.0	15.0	3.2	38	11	5.059	0.0591	9.763	-0.2372	15.098	0.0984	[illegible]
5.0	10.0	15.0	3.2	40	11	5.073	0.0731	10.177	0.1768	14.745	-0.2515	[illegible]
5.0	10.0	15.0	3.2	42	52	4.231	-0.7688	6.732	-3.2683	14.562	[illegible]	[illegible]
5.0	10.0	15.0	3.2	44	9	5.594	0.5938	8.338	-1.6621	14.755	-0.2475	[illegible]
5.0	10.0	15.0	3.2	46	10	4.937	-0.0635	9.543	-0.4565	15.389	[illegible]	[illegible]
5.0	10.0	15.0	5.0	6	56	4.840	-0.1598	9.755	-0.2451	15.101	[illegible]	[illegible]
5.0	10.0	15.0	5.0	8	11	5.126	0.1264	9.658	-0.3422	15.232	0.2226	[illegible]
5.0	10.0	15.0	5.0	10	11	4.512	-0.4876	9.775	-0.2252	15.080	[illegible]	[illegible]
5.0	10.0	15.0	5.0	12	56	4.069	-0.9310	9.384	-0.6156	15.161	0.1614	[illegible]
5.0	10.0	15.0	5.0	14	10	5.019	0.0191	8.601	-1.3990	15.066	0.0657	[illegible]
5.0	10.0	15.0	5.0	16	12	5.128	0.1278	10.163	0.1625	15.582	0.5822	0.5173
5.0	10.0	15.0	5.0	18	55	4.090	-0.9097	8.930	-1.0705	15.076	0.0764	1.4009
5.0	10.0	15.0	5.0	20	12	4.460	-0.5396	10.251	0.2511	15.174	0.1735	[illegible]
5.0	10.0	15.0	5.0	22	10	5.288	0.2879	8.908	-1.0919	14.444	[illegible]	[illegible]
5.0	10.0	15.0	5.0	24	58	3.228	-1.7719	10.254	0.2543	15.696	[illegible]	[illegible]
5.0	10.0	15.0	5.0	26	12	4.833	-0.1665	10.054	0.0540	[illegible]	[illegible]	[illegible]
5.0	10.0	15.0	5.0	28	10	5.038	0.0382	8.642	-1.3579	15.197	[illegible]	[illegible]
5.0	10.0	15.0	5.0	30	57	2.876	-2.1236	10.509	0.5094	15.566	0.5664	[illegible]
5.0	10.0	15.0	5.0	32	13	5.517	0.5169	10.998	0.9980	[illegible]	[illegible]	[illegible]
5.0	10.0	15.0	5.0	34	9	5.248	0.2484	8.318	-1.6818	15.057	[illegible]	[illegible]
5.0	10.0	15.0	5.0	36	58	2.599	-2.4012	8.742	-1.2580	15.467	[illegible]	[illegible]
5.0	10.0	15.0	5.0	38	10	5.418	0.4176	8.793	-1.2075	14.126	[illegible]	[illegible]
5.0	10.0	15.0	5.0	40	12	4.655	-0.3449	11.023	1.0228	15.276	0.2765	[illegible]
5.0	10.0	15.0	5.0	42	54	3.294	-1.7057	8.516	-1.4838	15.224	0.2233	[illegible]
5.0	10.0	15.0	5.0	44	11	5.200	0.2002	9.544	-0.4561	15.625	0.6249	0.7991
5.0	10.0	15.0	5.0	46	11	5.266	0.2660	10.326	0.3259	15.763	0.7635	[illegible]
5.0	10.0	15.0	8.0	6	52	6.301	1.3013	5.140	-4.8603	13.722	-1.2782	[illegible]
5.0	10.0	15.0	8.0	8	11	5.142	0.1424	9.832	-0.1685	15.449	[illegible]	[illegible]
5.0	10.0	15.0	8.0	10	10	5.359	0.3589	9.107	-0.8931	15.493	[illegible]	[illegible]
5.0	10.0	15.0	8.0	12	52	5.999	0.9985	6.450	-3.5495	14.152	[illegible]	[illegible]
5.0	10.0	15.0	8.0	14	10	4.654	-0.3459	9.131	-0.8689	[illegible]	[illegible]	[illegible]
5.0	10.0	15.0	8.0	16	10	5.672	0.6718	8.857	-1.1432	15.563	[illegible]	[illegible]
5.0	10.0	15.0	8.0	18	50	6.899	1.8991	3.271	-6.7288	12.842	[illegible]	[illegible]
5.0	10.0	15.0	8.0	20	10	5.396	0.3959	8.665	-1.3347	15.166	0.1665	1.4021
5.0	10.0	15.0	8.0	22	11	5.371	0.3705	9.464	-0.5361	15.966	[illegible]	[illegible]
5.0	10.0	15.0	8.0	24	56	4.872	-0.1282	9.717	-0.2835	15.529	[illegible]	[illegible]
5.0	10.0	15.0	8.0	26	14	5.323	0.3228	11.223	1.2234	15.059	[illegible]	[illegible]
5.0	10.0	15.0	8.0	28	9	4.790	-0.2096	8.242	-1.7585	14.793	-0.7070	[illegible]
5.0	10.0	15.0	8.0	30	50	6.245	1.2451	7.400	-2.5995	[illegible]	[illegible]	[illegible]

Table 6-4. RESIDT Data Period and Sensor Granularity Test Results (2 of 3)

SIMULATED BIASES X	Y	Z	GRANU-LARITY	DATA PERIOD (SECS)	ITERATIONS TO CONVERGE	X-COMP BIAS (MG)	X-COMP DEVIATION (MG)	Y-COMP BIAS (MG)	Y-COMP DEVIATION (MG)	Z-COMP BIAS (MG)	Z-COMP DEVIATION (MG)	TOTAL DEVIATION
0.00	0.00	0.00	0.00	32	10	0.335	1.3254	8.975	-1.0248	18.092	0.0321	1.9066
0.00	0.00	0.00	0.00	36	9	0.048	0.0853	8.702	-1.2476	15.879	0.8791	1.5698
0.00	0.00	0.00	0.00	36	51	5.186	0.1855	6.742	-1.2378	14.307	-0.6980	1.3347
0.00	0.00	0.00	0.00	38	11	5.585	0.5853	9.756	-0.2436	16.105	1.1047	1.2737
0.00	0.00	0.00	0.00	40	8	4.399	-0.6100	8.114	-1.8864	14.813	-0.1866	1.9914
0.00	0.00	0.00	0.00	42	60	3.541	-1.4594	8.651	-2.3492	14.782	-2.4178	3.4730
0.00	0.00	0.00	0.00	44	11	5.705	0.7845	8.866	-0.1337	15.894	0.6940	1.1969
0.00	0.00	0.00	0.00	46	11	5.941	0.9411	10.476	0.4757	15.629	0.6285	1.2276
0.00	0.00	0.00	0.00	48	71	2.361	-2.6394	5.380	-4.6201	16.912	1.5122	4.2403
0.00	0.00	0.00	14.00	6	13	4.258	-0.7421	10.170	0.1496	14.950	-0.0497	0.7529
0.00	0.00	0.00	14.00	8	12	4.459	-0.5411	10.452	0.4524	14.902	-0.0979	0.7123
0.00	0.00	0.00	14.00	10	66	1.089	-3.9111	6.773	-3.7730	17.654	2.6545	3.2563
0.00	0.00	0.00	14.00	12	14	3.934	-1.0664	11.209	1.2087	15.420	0.4196	1.4656
0.00	0.00	0.00	14.00	14	13	3.290	-1.7101	10.926	0.9258	15.128	0.1279	1.9944
0.00	0.00	0.00	14.00	16	66	2.056	-2.9440	13.368	3.3683	16.200	1.2003	1.6318
0.00	0.00	0.00	14.00	18	12	3.864	-1.1362	10.407	0.4068	14.963	-0.0374	1.2034
0.00	0.00	0.00	14.00	20	10	4.447	-0.5525	8.798	-1.2019	14.511	-0.4867	1.4102
0.00	0.00	0.00	14.00	22	109	0.070	-4.9299	12.665	2.6632	16.419	0.4194	5.7811
0.00	0.00	0.00	14.00	24	14	5.127	0.1269	10.867	0.8610	15.451	0.4514	0.9857
0.00	0.00	0.00	14.00	26	23	3.494	-1.5057	13.357	3.3569	15.568	0.5684	3.7227
0.00	0.00	0.00	14.00	28	82	3.493	-1.5075	24.733	14.7326	26.731	11.7306	13.0194
0.00	0.00	0.00	14.00	30	10	2.171	-2.8287	9.013	-0.9825	16.288	1.2880	3.2598
0.00	0.00	0.00	14.00	32	9	5.776	0.7757	7.606	-2.3943	15.543	0.5431	2.5748
0.00	0.00	0.00	14.00	34	113	-0.271	-5.2715	16.742	6.7415	18.459	3.4291	9.2303
0.00	0.00	0.00	14.00	36	13	4.522	-0.7778	10.742	0.7415	16.040	1.0396	1.4476
0.00	0.00	0.00	14.00	38	11	2.404	-2.8945	10.162	0.1621	15.944	0.9439	2.6712
0.00	0.00	0.00	14.00	40	124	-0.798	-5.7981	28.562	18.5621	23.044	8.0437	21.0445
0.00	0.00	0.00	14.00	42	8	5.484	0.4841	6.516	-3.4841	15.510	0.5104	3.5544
0.00	0.00	0.00	14.00	44	8	5.245	-2.7552	7.933	-2.0673	16.748	-1.7481	3.8627
0.00	0.00	0.00	14.00	46	154	45.034	2.0335	54.534	-5.4659	77.480	-2.1201	6.2053
0.00	0.00	0.00	14.00	48	299	40.016	0.0157	59.815	-0.1855	79.990	-0.0102	0.1464
0.00	0.00	0.00	1.66	6	47	39.936	-0.0641	60.151	0.1514	79.976	-0.0256	0.1664
0.00	0.00	0.00	1.66	10	152	42.739	2.7393	53.820	-6.1717	77.269	-2.4313	4.1767
0.00	0.00	0.00	1.66	12	501	39.899	-0.1011	58.505	-3.4959	80.031	0.0311	3.4266
0.00	0.00	0.00	1.66	14	58	40.156	0.1559	60.063	0.0623	79.932	-0.0450	0.1740
0.00	0.00	0.00	1.66	16	156	41.420	1.4197	55.415	-4.5884	78.231	-1.7691	3.1185
0.00	0.00	0.00	1.66	18	501	39.913	-0.0875	56.105	-3.8950	79.811	-0.1884	3.4006
0.00	0.00	0.00	1.66	20	501	39.931	-0.0688	53.688	-6.3121	79.799	-0.2008	6.3157
0.00	0.00	0.00	1.66	22	150	42.474	2.4741	53.832	-6.1680	77.696	-2.3042	7.0338
0.00	0.00	0.00	1.66	24	501	39.985	-0.0149	55.165	-4.8350	79.982	-0.1185	4.6365
0.00	0.00	0.00	1.66	26	37	40.082	0.0823	59.137	-0.2628	80.027	0.0267	0.2767
0.00	0.00	0.00	1.66	28	154	41.585	1.5846	55.462	-4.5375	78.166	-1.8337	5.1442
0.00	0.00	0.00	1.66	30	34	40.079	0.0792	59.991	-0.0087	79.854	-0.1460	0.1663
0.00	0.00	0.00	1.66	32	10	39.999	-0.0011	59.852	-0.1475	79.871	-0.1288	0.1939
0.00	0.00	0.00	1.66	34	152	42.075	2.0753	54.960	-5.0398	78.018	-1.9821	5.7996
0.00	0.00	0.00	1.66	36	501	39.532	-0.4683	49.059	-10.9406	79.662	-0.3378	10.9559
0.00	0.00	0.00	1.66	38	15	39.876	-0.1237	60.182	0.1820	79.910	-0.0903	0.2373
0.00	0.00	0.00	1.66	40	151	42.416	2.4156	54.411	-5.5885	78.005	-1.9943	6.4066
0.00	0.00	0.00	1.66	42	501	39.955	-0.0454	57.042	-2.9272	80.010	0.0100	2.9382
0.00	0.00	0.00	1.66	44	501	40.386	0.3863	60.046	0.0732	79.930	-0.0101	0.3955
0.00	0.00	0.00	1.66	46	155	41.915	1.9155	54.873	-5.1272	78.058	-1.9425	5.8078
0.00	0.00	0.00	3.32	6	8	39.916	-0.0837	56.228	-3.7723	79.885	-0.1147	3.7730
0.00	0.00	0.00	3.32	8	18	39.979	-0.0209	59.765	-0.2186	79.921	-0.0737	0.7794
0.00	0.00	0.00	3.32	10	158	40.926	0.9260	56.158	-3.8420	78.283	-1.7171	4.1984
0.00	0.00	0.00	3.32	12	229	39.898	-0.1024	59.105	-0.3948	80.022	0.0218	0.4085
0.00	0.00	0.00	3.32	14	98	40.015	-0.0149	60.327	0.3265	79.847	-0.1534	0.3611
0.00	0.00	0.00	3.32	16	153	42.110	2.1098	54.614	-5.3863	77.908	-2.0921	6.1514
0.00	0.00	0.00	3.32	18	59	39.877	-0.1233	59.012	-0.9275	79.912	-0.0883	0.9398
0.00	0.00	0.00	3.32	20	501	40.198	0.1984	56.127	-3.8726	80.017	0.0175	3.8777
0.00	0.00	0.00	3.32	22	153	41.514	1.5135	55.345	-4.6551	78.093	-1.9068	5.4236
0.00	0.00	0.00	3.32	24	43	40.260	0.2598	59.292	-0.7078	80.021	0.0207	0.7345
0.00	0.00	0.00	3.32	26	73	39.906	-0.0935	59.700	-0.3003	79.871	-0.1286	0.3398
0.00	0.00	0.00	3.32	28	152	41.341	1.3407	54.126	-5.8738	77.977	-2.0229	6.3524
0.00	0.00	0.00	3.32	30	39	39.779	-0.2208	59.976	-0.0236	79.881	-0.1190	0.2520
0.00	0.00	0.00	3.32	32	7	40.145	0.1654	60.143	0.1431	80.149	0.1687	0.2448
0.00	0.00	0.00	3.32	34	153	41.880	1.8801	55.921	-4.0788	78.212	-1.8972	4.8542
0.00	0.00	0.00	3.32	36	501	40.061	0.0605	56.469	-3.5307	79.508	-0.4920	3.5653
0.00	0.00	0.00	3.32	38	13	39.940	-0.0595	59.285	-0.7152	79.897	-0.1031	0.7250
0.00	0.00	0.00	3.32	40	154	40.460	0.4601	54.424	-5.5766	78.402	-1.5182	4.8428
0.00	0.00	0.00	3.32	42	501	40.419	0.4186	59.694	-0.3059	80.371	0.3712	0.6317
0.00	0.00	0.00	3.32	44	13	40.007	0.0068	60.219	0.2190	79.559	-0.4410	0.4926
0.00	0.00	0.00	3.32	46	136	44.467	4.4668	46.269	-13.7309	76.218	-3.7622	14.9263
0.00	0.00	0.00	14.00	6	31	40.203	0.2831	58.789	-1.2108	80.776	0.7759	1.4657
0.00	0.00	0.00	14.00	8	1	40.091	0.0910	58.528	-1.4718	80.416	0.4159	1.5495
0.00	0.00	0.00	14.00	10	141	44.174	4.1737	48.348	-11.6524	77.057	-2.9431	12.7225
0.00	0.00	0.00	14.00	12	74	38.875	-1.1254	58.845	-1.1553	80.099	0.0987	1.6139
0.00	0.00	0.00	14.00	14								

Table 6-4. RESIDT Data Period and Sensor Granularity Test Results (3 of 3)

SIMULATED BIASES X	Y	Z	GRANULARITY	DATA PERIOD (SECS)	ITERATIONS TO CONVERGE	X-COMP BIAS (MG)	DEVIATION (MG)	Y-COMP BIAS (MG)	DEVIATION (MG)	Z-COMP BIAS (MG)	DEVIATION (MG)	TOTAL DEVIATION
40.0	60.0	80.0	14.0	16	14	40.919	0.9190	58.023	-1.9769	80.624	0.6238	2.2676
40.0	60.0	80.0	14.0	18	135	45.328	5.3284	44.952	-15.0478	75.615	-4.3250	16.5386
40.0	60.0	80.0	14.0	20	12	39.310	-0.6898	56.003	-3.9968	79.210	-0.7896	4.1320
40.0	60.0	80.0	14.0	22	501	41.069	1.0692	45.494	-14.5063	80.775	0.7747	14.5663
40.0	60.0	80.0	14.0	24	133	42.988	2.9880	45.093	-14.9071	76.385	-3.6149	15.6274
40.0	60.0	80.0	14.0	26	10	39.019	-0.9809	54.552	-5.4475	80.442	0.4417	5.5527
40.0	60.0	80.0	14.0	28	33	40.466	0.4658	59.744	-0.2558	79.781	-0.2138	0.5747
40.0	60.0	80.0	14.0	30	137	44.427	4.4274	46.835	-13.1647	76.463	-3.5373	14.3326
40.0	60.0	80.0	14.0	32	52	40.993	0.9926	60.184	0.1839	79.932	-0.0677	1.0117
40.0	60.0	80.0	14.0	34	52	38.011	-1.9887	61.526	1.5262	79.682	-0.3178	2.5253
40.0	60.0	80.0	14.0	36	126	43.603	3.6033	40.578	-19.4220	75.035	-4.9646	20.3570
40.0	60.0	80.0	14.0	38	43	40.490	0.4901	58.055	-1.9446	79.673	-0.3268	2.0319
40.0	60.0	80.0	14.0	40	8	40.040	0.0395	56.119	-3.8807	75.553	-0.4472	3.9366
40.0	60.0	80.0	14.0	42	124	45.970	5.9699	45.310	-14.6898	75.304	-4.6956	16.5372
40.0	60.0	80.0	14.0	44	501	41.279	1.2790	41.959	-18.0408	79.733	-0.2668	18.0680
40.0	60.0	80.0	14.0	46	16	40.180	0.1796	61.653	1.6533	79.295	-0.7049	1.8062
40.0	60.0	80.0	5.0	6	157	41.608	1.6078	54.838	-5.1610	78.202	-1.7976	5.6975
40.0	60.0	80.0	5.0	8	110	40.127	0.1268	59.683	-0.3165	80.232	0.2325	0.4127
40.0	60.0	80.0	5.0	10	40	39.513	-0.4873	59.798	-0.2022	80.080	0.0801	0.5336
40.0	60.0	80.0	5.0	12	158	40.758	0.7580	54.582	-5.4161	78.314	-1.6860	5.7243
40.0	60.0	80.0	5.0	14	47	40.019	0.0185	58.576	-1.4244	80.065	0.0651	1.4260
40.0	60.0	80.0	5.0	16	49	40.128	0.1276	60.136	0.1361	80.582	0.5815	0.6107
40.0	60.0	80.0	5.0	18	157	40.720	0.7199	54.194	-5.8059	78.264	-1.7357	6.1024
40.0	60.0	80.0	5.0	20	501	39.284	-0.7161	52.953	-7.0469	80.004	0.0043	7.0832
40.0	60.0	80.0	5.0	22	48	40.288	0.2884	58.936	-1.0644	79.945	-0.0546	1.1241
40.0	60.0	80.0	5.0	24	158	39.864	-0.1359	55.333	-4.6673	78.785	-1.2145	4.8246
40.0	60.0	80.0	5.0	26	147	39.833	-0.1669	60.027	0.0270	79.948	-0.0525	0.1770
40.0	60.0	80.0	5.0	28	7	40.027	0.0273	58.630	-1.3697	80.176	0.1759	1.3812
40.0	60.0	80.0	5.0	30	158	39.391	-0.6094	55.710	-4.2899	78.708	-1.2924	4.5216
40.0	60.0	80.0	5.0	32	39	40.516	0.5163	60.968	0.9679	80.877	0.8771	1.4046
40.0	60.0	80.0	5.0	34	16	40.248	0.2481	58.299	-1.7014	80.056	0.0561	1.7203
40.0	60.0	80.0	5.0	36	159	39.115	-0.8851	54.052	-5.9480	78.686	-1.3137	6.1553
40.0	60.0	80.0	5.0	38	501	40.283	0.2832	55.382	-4.6178	79.057	-0.9425	4.7215
40.0	60.0	80.0	5.0	40	19	39.656	-0.3443	61.047	1.0472	80.277	0.2771	1.1366
40.0	60.0	80.0	5.0	42	156	39.672	-0.3275	54.019	-5.9808	78.539	-1.4614	6.1654
40.0	60.0	80.0	5.0	44	43	40.199	0.1990	59.516	-0.4844	80.624	0.6242	0.8148
40.0	60.0	80.0	5.0	46	14	40.266	0.2655	60.309	0.3090	80.763	0.7630	0.8650
40.0	60.0	80.0	8.0	6	157	41.775	1.7753	54.338	-5.6621	77.749	-2.2508	6.3465
40.0	60.0	80.0	8.0	8	501	39.621	-0.3791	58.910	-1.0897	79.898	-0.1023	1.1563
40.0	60.0	80.0	8.0	10	501	39.971	-0.0289	60.719	0.7195	80.077	0.0775	0.7242
40.0	60.0	80.0	8.0	12	154	42.473	2.4726	53.388	-6.6119	77.199	-2.8013	7.5947
40.0	60.0	80.0	8.0	14	501	39.925	-0.0748	47.541	-12.4588	79.536	-0.4640	12.4677
40.0	60.0	80.0	8.0	16	501	39.750	-0.2503	60.963	0.9626	80.523	0.5233	1.1239
40.0	60.0	80.0	8.0	18	157	41.618	1.6180	54.749	-5.2515	77.937	-2.0628	5.8695
40.0	60.0	80.0	8.0	20	501	39.888	-0.1124	48.611	-11.3885	79.530	-0.4696	11.3988
40.0	60.0	80.0	8.0	22	501	39.344	-0.6562	49.730	-10.2698	79.340	-0.6601	10.3119
40.0	60.0	80.0	8.0	24	152	42.609	2.6089	53.765	-6.2345	77.604	-2.3957	7.1704
40.0	60.0	80.0	8.0	26	501	39.728	-0.2715	53.630	-6.3703	79.723	-0.2769	6.3821
40.0	60.0	80.0	8.0	28	95	40.053	0.0533	60.393	0.3926	80.354	0.3538	0.5311
40.0	60.0	80.0	8.0	30	154	41.789	1.7887	55.711	-4.2890	78.040	-1.9598	5.0434
40.0	60.0	80.0	8.0	32	307	39.590	-0.4105	61.948	1.9482	80.656	0.6555	2.0961
40.0	60.0	80.0	8.0	34	13	39.233	-0.7665	61.313	1.3126	80.640	0.6397	1.6491
40.0	60.0	80.0	8.0	36	144	44.706	4.7065	51.714	-8.2865	76.387	-3.6126	10.1914
40.0	60.0	80.0	8.0	38	501	39.781	-0.2191	44.388	-15.6123	80.073	0.0729	15.6140
40.0	60.0	80.0	8.0	40	26	39.660	-0.3399	62.236	2.2357	78.996	-1.0042	2.4743
40.0	60.0	80.0	8.0	42	139	41.328	1.3283	45.980	-14.0198	74.807	-5.1926	15.0054
40.0	60.0	80.0	8.0	44	501	38.461	-1.5393	51.628	-8.3724	79.434	-0.5659	8.5315
40.0	60.0	80.0	8.0	46	18	40.988	0.9878	62.709	2.7088	80.269	0.2688	2.8958

The column headed "Total Deviation" reports the root-mean-square (RMS) magnitude of the deviation in units of milli-gauss, and total deviation defined here is the same as "accuracy" as defined in Equation 6-1.

The test data spanned the perigee time and was taken from a constant 1000-second (16 minutes, 40 seconds) interval for all tests. Thus, as the simulated data period is increased, the total number of data points is decreased to maintain a constant total time interval of 1000 seconds.

Figures 6-1 through 6-5 show the simulated accuracy (mG) of the RESIDG algorithm for the granularity values of 1.6, 3.2, 5.0, 8.0, and 14.0 mG over the range of data periods simulated (6 to 42 seconds). Figures 6-1 and 6-5 are plots of the values in the Total Deviation column in Table 6-3. These figures show the striking correlation between bias determination accuracy and data period. The accuracy is observed to be periodic with a period of 6 seconds (the spin period of the AMPTE spacecraft) for all resolutions. Also, the amplitude of oscillation generally is independent of the data period for a given resolution. The peaks of the oscillations occur at 6, 12, 18, 24, 30, 36, and 42 seconds. In a few cases, peaks appear as shoulders and are not completely distinct. When the data period is a multiple of 6 seconds, each magnetometer data sample is nearly the same as in previous samples; thus, this results in poor geometry for the least-squares algorithms. The best geometry occurs when successive readings differ by 180 degrees (e.g., a 9-second data period).

The results using the RESIDT algorithm qualitatively were the same as for the RESIDG algorithm. The behavior of the RESIDT algorithm showed the same oscillatory behavior as a function of data period.

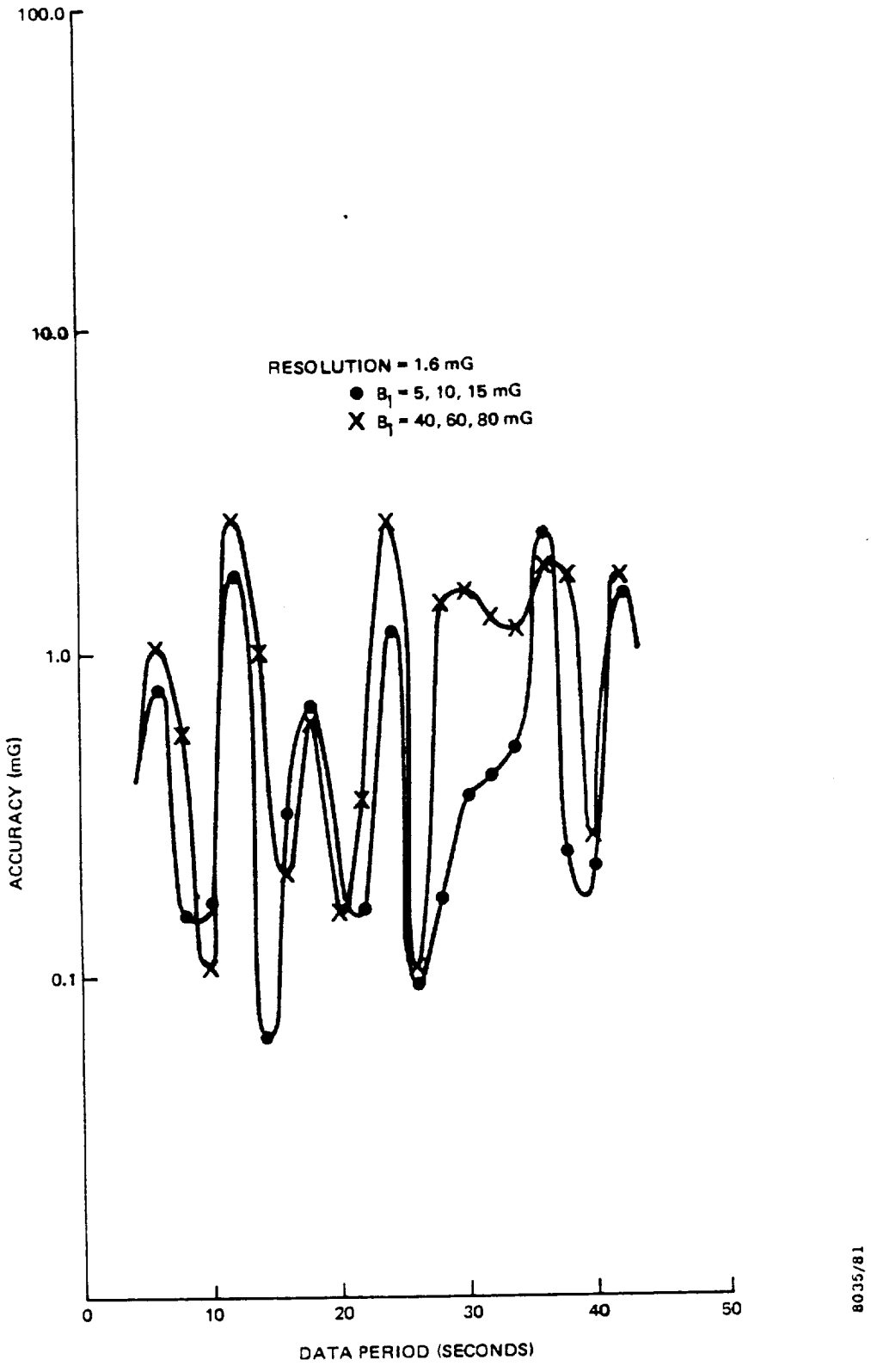

Figure 6-1. Simulated Accuracy of RESIDG for Granularity Value of 1.6 mG

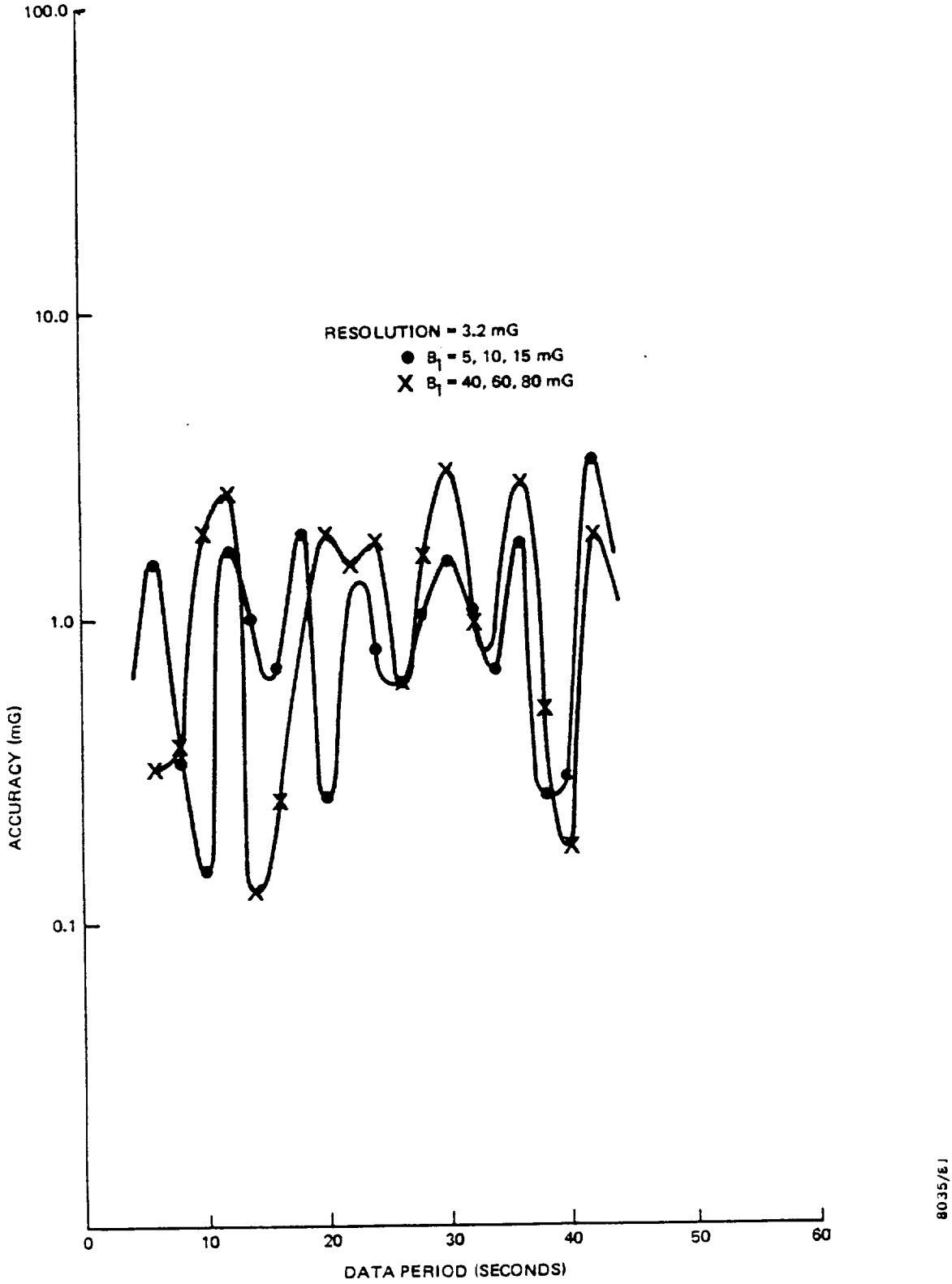

Figure 6-2. Simulated Accuracy of RESIDG for Granularity Value of 3.2 mG

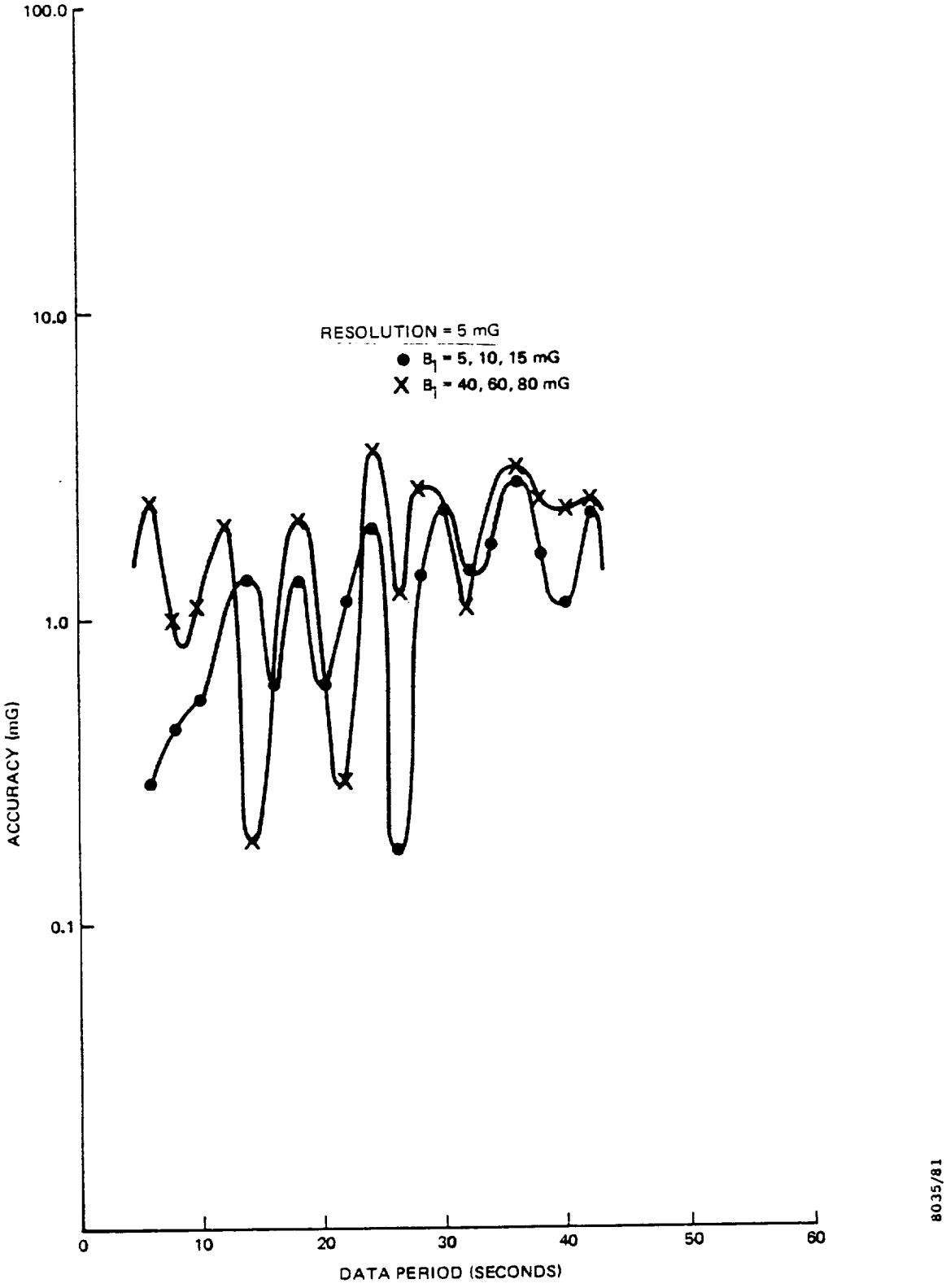

Figure 6-3. Simulated Accuracy of RESIDG for Granularity Value of 5.0 mG

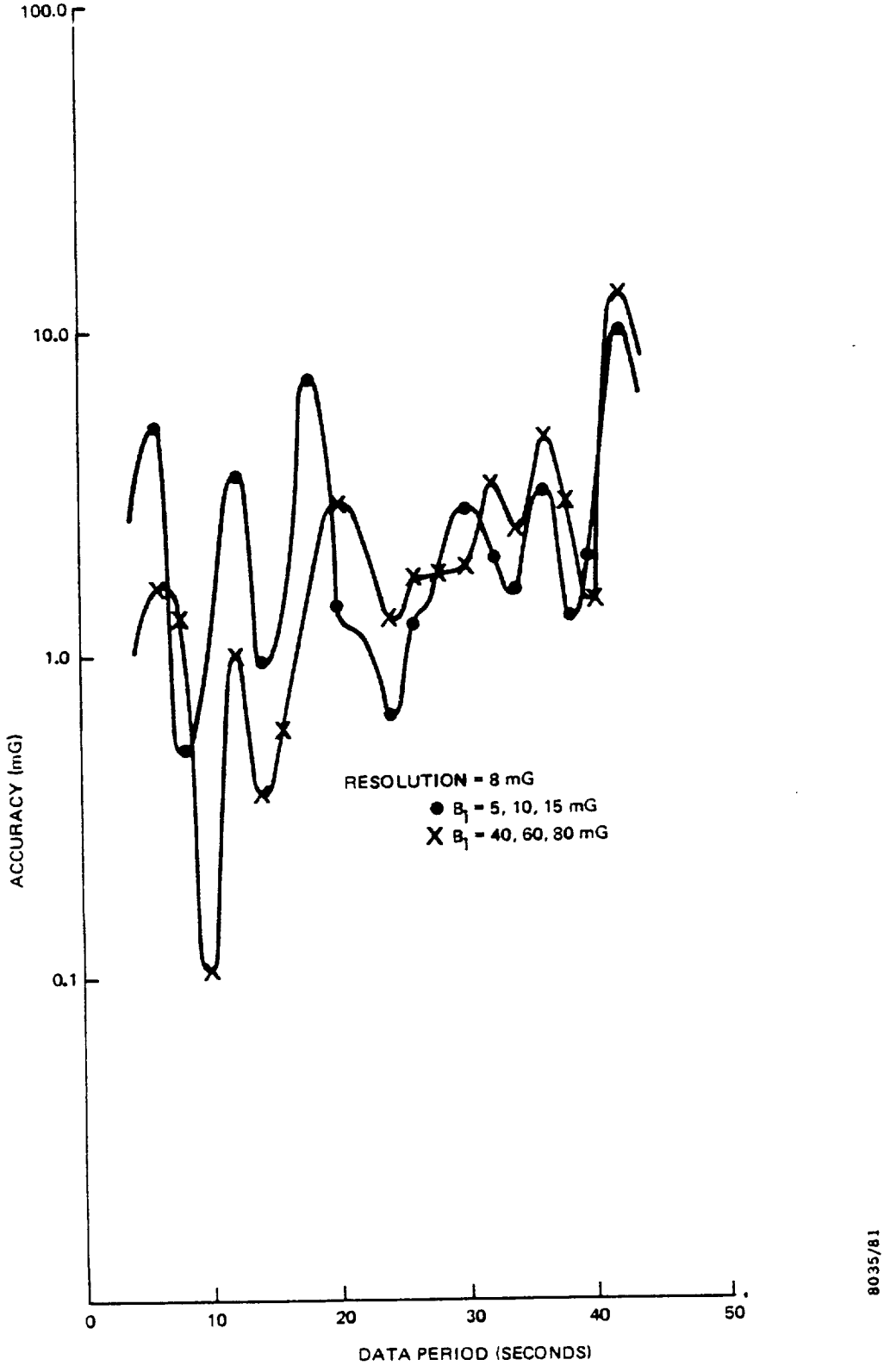

Figure 6-4. Simulated Accuracy of RESIDG for Granularity Value of 8.0 mG

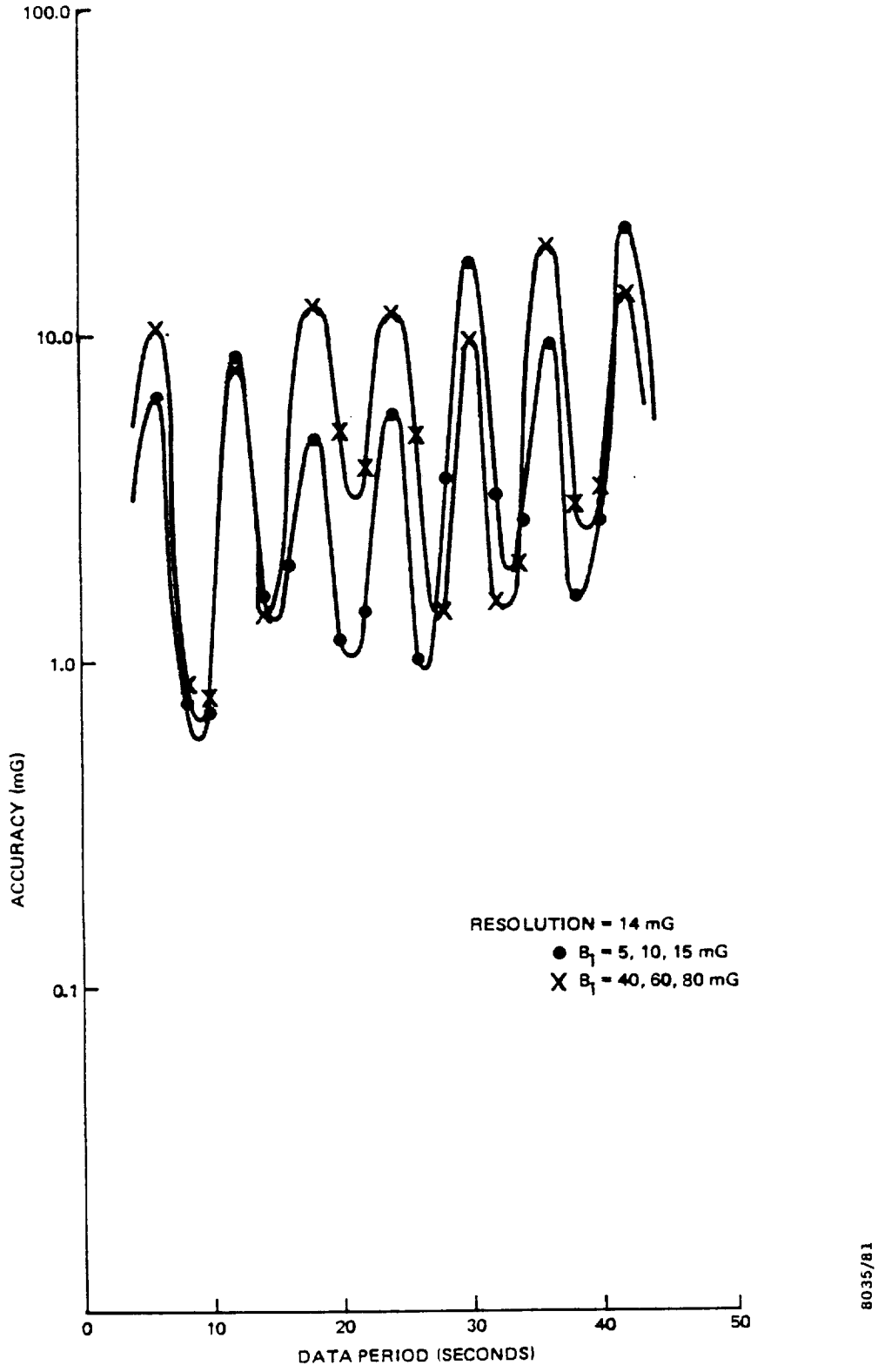

Figure 6-5. Simulated Accuracy of RESIDG for Granularity Value of 14.0 mG

Figures 6-6 and 6-7 show both the RESIDG and RESIDT results for 1.6 mG granularity and the 5, 10, 15 mG and 40, 60, 80 mG bias vectors. For the 5, 10, 15 mG case, both algorithms give almost identical results, with RESIDT giving better results near the peaks. For the 40, 60, 80 mG case, RESIDG gives far better results than RESIDT. This is because the RESIDG initial bias estimate is much more accurate than that used by RESIDT for large biases. However, both RESIDT and RESIDG give good results for the "good geometry" data periods (data periods that result in minimum values of the oscillation in accuracy), even when the relatively large bias vector of 40, 60, 80 mG is present.

With regard to accuracy versus sensor granularity alone, no universal curve appears to describe accuracy versus granularity for a specific data period (Figure 6-8). However, accuracy gets worse as the granularity increases, and granularities greater than 5 mG lead to large errors for the 6- and 12-second data periods. Figure 6-8 does enable one significant conclusion. The overall accuracy is much more dependent on a judicious choice of data period rather than on sensor granularity. Even for a "poor" sensor granularity value (e.g., 8 mG or 14 mG), the accuracy of the RESIDG algorithm is good for data periods that are not multiples of the spacecraft spin rate (e.g., 8-, 10-, or 14-second data periods illustrated in Figure 6-8).

6.5 NONPROXIMITY TO PERIGEE TEST RESULTS

Several tests were run to determine the effect of varying the data collection time period (1000-second duration) over different locations within the simulated highly elliptical AMPTE orbit. Specifically, the purpose of the test was to determine the effects of not spanning perigee time during the data collection period.

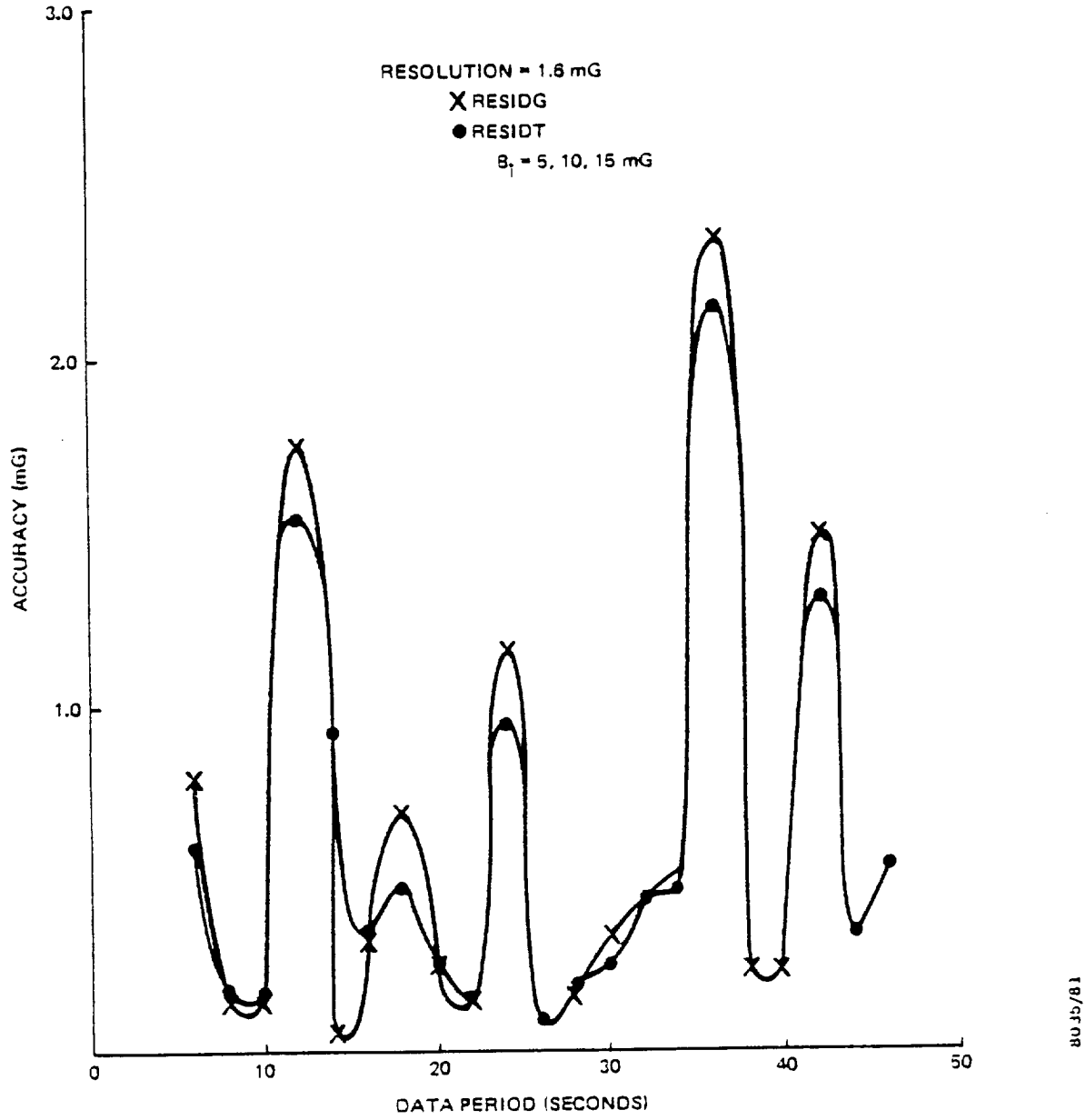

Figure 6-6. RESIDG and RESIDT Results for 1.6 mG Granularity (Bias Vector = 5, 10, 15 mG)

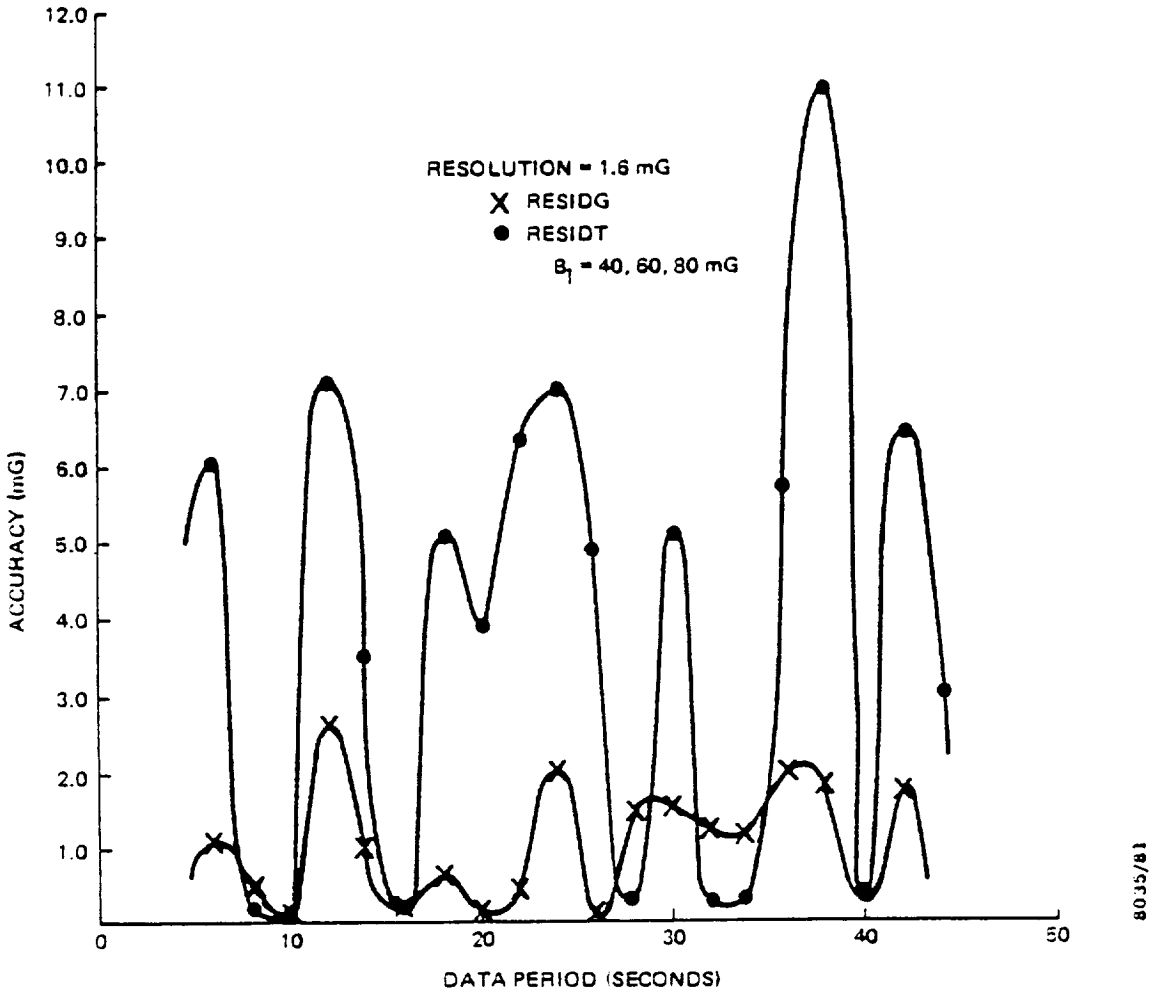

Figure 6-7. RESIDG and RESIDT Results for 1.6 mG Granularity (Bias Vector = 40, 60, 80 mG)

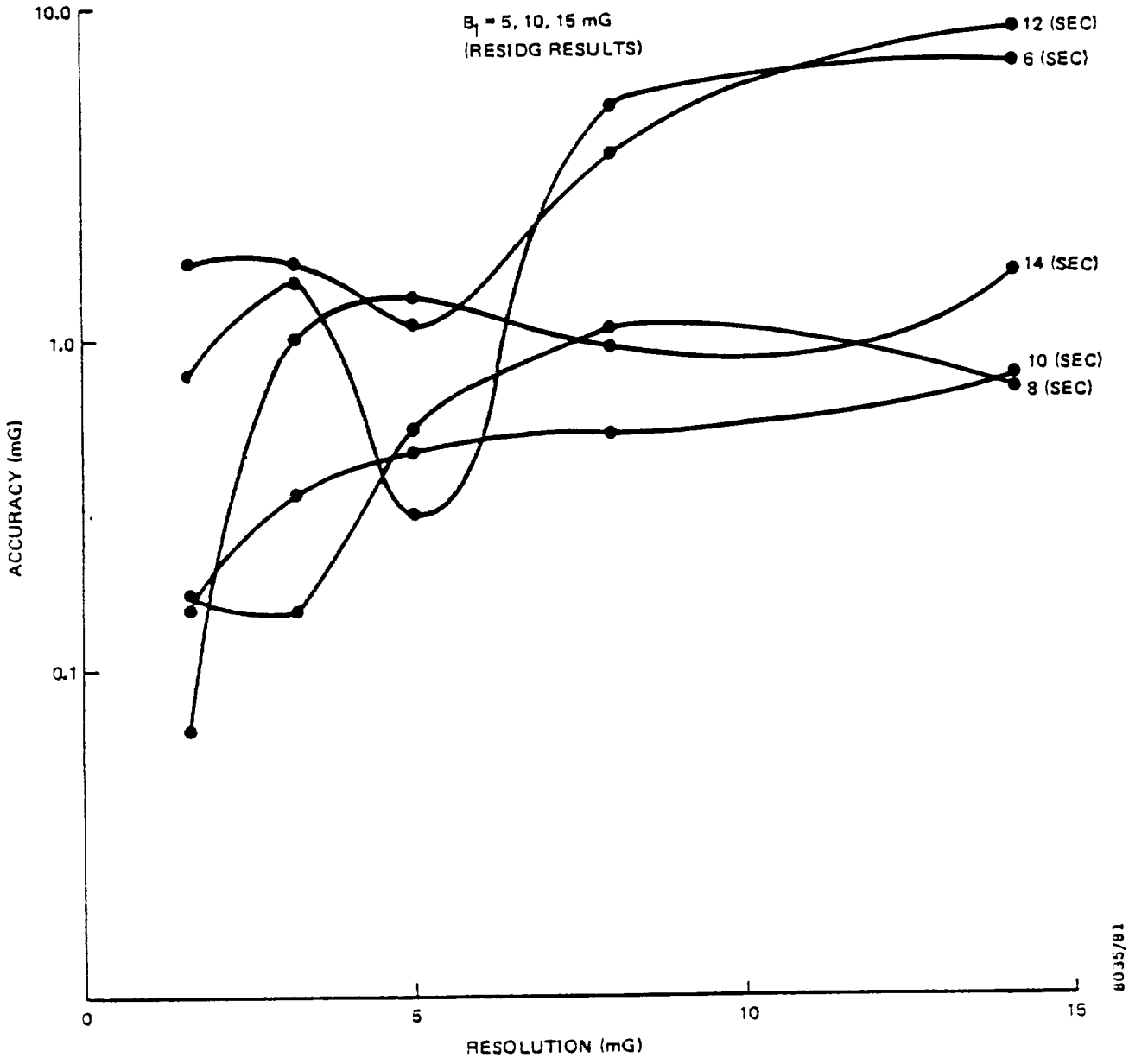

Figure 6-8. Accuracy Versus Sensor Granularity

All tests used a 1000-second data collection period (16 minutes, 40 seconds) beginning at times (YYMMDD.HHMM) ranging from 830901.0000 to 830901.0130 (Tables 6-5 and 6-6). The perigee time assumed was 830901.0138. For each simulation, at 15-minute intervals (830901.0000, 830901.0015, ... 830901.0130), a sensor granularity of 3.2 mG and a data period of 10 seconds were used. Tests were performed for x, y, z bias vectors of 5, 10, 15 and 40, 60, 80 mG. Note that the test with the starting time of 830901.0130 is the one that spans the perigee time. "Accuracy" in Tables 6-5 and 6-6 is the same as defined by Equation (6-1).

Figure 6-9 presents a plot of the computed accuracy versus start time. Figure 6-9 illustrates that accuracy is indeed dependent on proximity to perigee. Data taken at a starting time 40 minutes before perigee (or closer to perigee) was much more accurate than data taken 1 hour or more before perigee.

Two other observations are apparent from Figure 6-9. First, accuracy is dependent on bias magnitude. For the 10-second simulated data period the results for the 5, 10, 15 mG bias vector were in general half an order of magnitude (or more) better than the 40, 60, 80 mG case. Even for data taken 1 hour away from perigee, the accuracy for the 5, 10, 15 mG bias case was acceptable on the order of a few milligauss. The second additional observation is that the RESIDG and RESIDT algorithms performed roughly equivalently; neither algorithm was significantly superior to the other either close to or away from perigee.

6.6 SENSOR MISALIGNMENT TEST RESULTS

Several tests were made to determine the effects of magnetometer misalignment. The x-axis was misaligned in the x-y plane toward the y-axis; the y-axis was misaligned in the

Table 6-5. RESIDG Orbit Dependence Results

START TIME (HHMMSS)	SIMULATED BIASES (mG)			COMPUTED BIASES (mG)			DEVIATIONS (mG)			ACCURACY (mG)
	X	Y	Z	X	Y	Z	X	Y	Z	
.013000	5	10	15	5.00	10.01	14.81	.00	.01	−.19	.19
	40	60	80	39.95	59.17	79.84	−.05	−.83	−.16	.85
.011500	5	10	15	4.97	10.33	14.99	−.03	.33	−.01	.33
	40	60	80	40.13	59.34	79.86	.13	−.66	−.14	.69
.010000	5	10	15	4.86	9.59	15.05	−.14	−.41	.05	.44
	40	60	80	39.67	52.30	79.86	−.33	−7.70	−.14	7.70
.004500	5	10	15	5.08	5.33	15.01	.08	−4.67	.01	4.67
	40	60	80	37.65	46.78	75.27	−2.35	−13.22	−4.73	14.23
.003000	5	10	15	4.98	7.24	14.95	.02	−2.76	−.05	2.76
	40	60	80	35.69	48.74	71.42	−4.30	−11.27	−8.58	14.80
.001500	5	10	15	4.96	7.83	14.92	−.04	−2.17	−.08	2.17
	40	60	80	35.42	49.35	70.28	−4.58	−10.65	−9.72	15.12
.000000	5	10	15	4.69	8.31	14.51	−.31	−1.69	−.49	1.79
	40	60	80	34.84	49.67	69.60	−5.16	−10.33	−10.40	15.54

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GRANULARITY = 3.2 mG

DATA PERIOD = 10.0 SECONDS

PERIGEE TIME = .013800

DATA COLLECTION PERIOD = 1000 SECONDS

Table 6-6. RESIDT Orbit Dependence Results

START TIME (HHMMSS)	SIMULATED BIASES (mG)			COMPUTED BIASES (mG)			DEVIATIONS (mG)			ACCURACY (mG)
	X	Y	Z	X	Y	Z	X	Y	Z	
.013000	5	10	15	5.00	10.02	14.81	−.00	.02	−.19	.19
	40	60	80	39.96	58.91	79.86	−.04	−1.09	−.15	1.10
.011500	5	10	15	4.97	10.40	15.00	−.03	.40	.00	.40
	40	60	80	40.16	59.92	79.93	.16	−.08	−.07	.19
.010000	5	10	15	4.86	10.02	15.05	−.14	.02	.05	.15
	40	60	80	39.86	61.21	80.20	−.14	1.21	.20	1.23
.004500	5	10	15	5.08	6.73	15.00	.08	−3.27	.00	3.27
	40	60	80	40.20	46.38	80.10	.20	−13.63	.10	13.63
.003000	5	10	15	5.00	8.33	14.98	.00	−1.67	−.02	1.67
	40	60	80	40.00	46.48	79.97	.00	−13.52	−.03	13.52
.001500	5	10	15	4.99	7.76	15.03	−.01	−2.24	.03	2.24
	40	60	80	39.64	46.60	80.14	−.36	−13.40	.14	13.41
.000000	5	10	15	4.62	8.67	14.79	−.38	−1.33	−.21	1.40
	40	60	80	39.90	46.56	79.68	−.10	−13.44	−.32	13.45

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GRANULARITY = 3.2 mG

DATA PERIOD = 10.0 SECONDS

PERIGEE TIME = .013800

DATA COLLECTION PERIOD = 1000 SECONDS

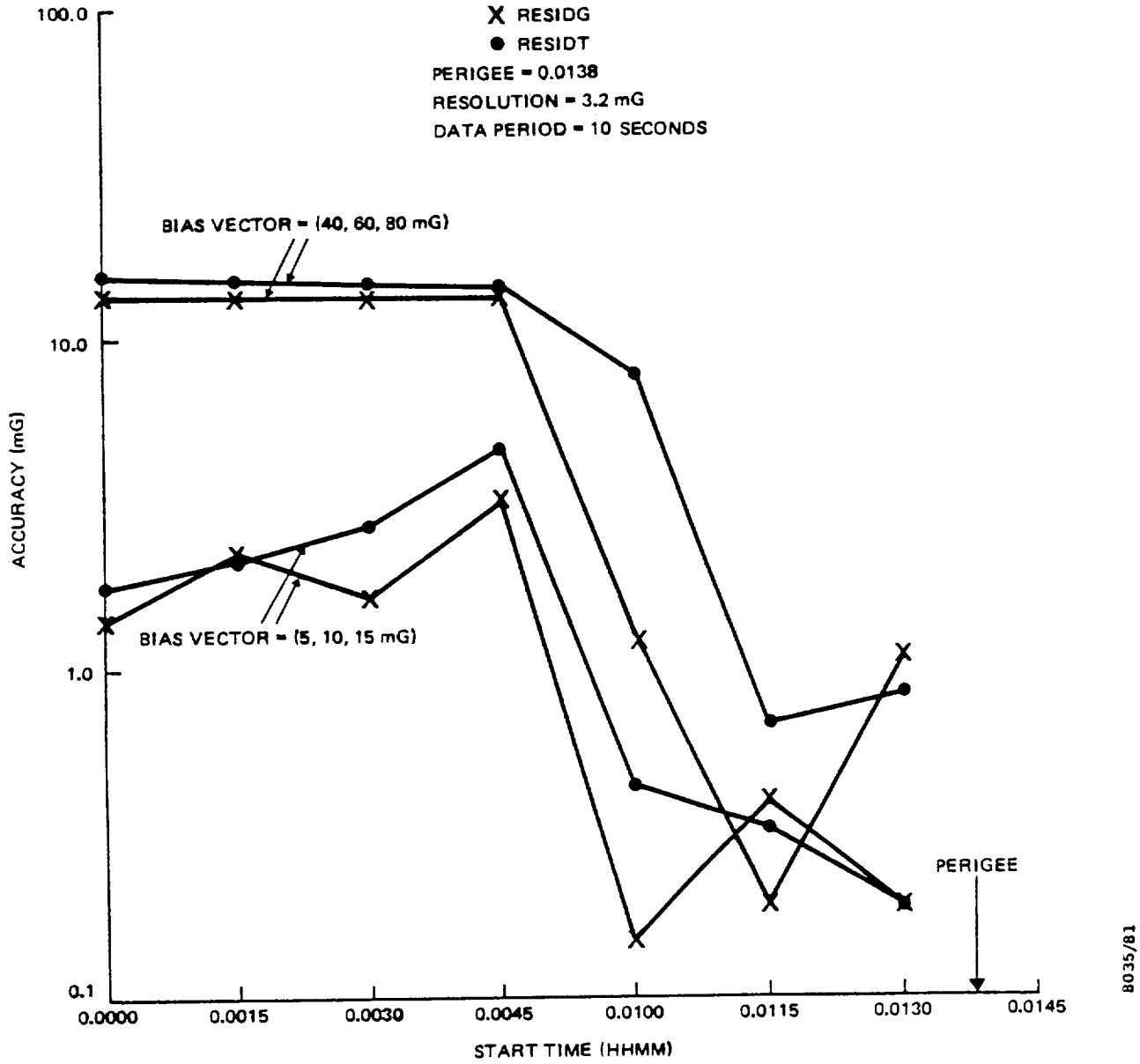

Figure 6-9. Computed Accuracy Versus Start Time for RESIDG and RESIDT

x-y plane toward the x-axis; the y-axis was misaligned in the y-z plane toward the z-axis; and, the y-axis was misaligned out of the x-y and y-z planes. Table 6-7 shows the results of these tests. The tests were run with an x, y, z component bias of 5, 10, and 15 mG; 3.2 mG sensor granularity; and a data period of 10 seconds.

The tests in Table 6-7 show that as the x-axis is rotated toward the y-axis in the x-y plane, the error seen is almost linear as a function of the angle (Figure 6-10). In this situation, the x and y biases are coupled together, while the z bias is almost unaffected by the misalignment. This occurs because the bias determination algorithms are attempting to adjust the biases such that the magnitude of the measured field in the x-y plane is the same as the computed field. Because the z-bias has no effect on the component of the field in the x-y plane, it is not adjusted erroneously in an attempt to compensate for the misalignment; the x and y biases are adjusted erroneously.

The same effect was noticed when the y-axis was rotated in the x-y plane toward the x-axis. When the y-axis was rotated toward the z-axis in the y-z plane, the y and z biases were adjusted by the algorithms to compensate for misalignment (Table 6-7). When a general rotation of the y-axis was performed such that the y-axis lies out of both the x-y and y-z planes, all biases were adjusted.

Table 6-7. Effects of Magnetometer Misalignment

MISALIGNMENT (DEGREES)	COMPUTED BIASES (mG)			DEVIATIONS (mG)			ACCURACY (mG)	ALGORITHM
	X	Y	Z	X	Y	Z		
X-AXIS (TOWARD Y-AXIS IN X-Y PLANE)								
1	3.80	10.32	14.91	−1.20	.32	−.10	1.24	RESIDG
	3.80	10.36	14.90	−1.20	.36	−.10	1.25	RESIDT
2	2.60	10.48	15.00	−2.40	.47	.00	2.45	RESIDG
	2.60	10.45	14.99	−2.40	.45	.01	2.45	RESIDT
3	1.58	10.69	14.98	−3.43	.69	−.02	3.49	RESIDG
	1.57	10.67	14.98	−3.43	.67	−.02	3.49	RESIDT
4	.12	11.11	15.05	−4.88	1.11	.05	5.01	RESIDG
	.12	11.08	15.05	−4.88	1.08	.05	5.00	RESIDT
5	−.80	11.32	15.19	−5.80	1.32	.19	5.95	RESIDG
	−.80	11.30	15.19	−5.80	1.30	.19	5.95	RESIDT
Y-AXIS (TOWARD X-AXIS IN X-Y PLANE)								
1	4.00	10.14	14.79	−1.00	.14	−.21	1.03	RESIDG
	4.00	10.15	14.79	−1.00	.15	−.21	1.04	RESIDT
2	2.72	10.18	14.75	−2.29	.18	−.25	2.31	RESIDG
	2.71	10.20	14.75	−2.29	.20	−.25	2.31	RESIDT
3	1.51	9.76	14.62	−3.49	−.24	−.38	3.52	RESIDG
	1.51	9.79	14.62	−3.49	−.21	−.38	3.52	RESIDT
4	.40	9.65	14.49	−4.60	−.35	−.51	4.64	RESIDG
	.40	9.66	14.49	−4.60	−.34	−.51	4.64	RESIDT
5	−.71	9.35	14.44	−5.71	−.65	−.56	5.78	RESIDG
	−.72	9.36	14.44	−5.72	−.64	−.56	5.78	RESIDT
Y-AXIS (TOWARD Z-AXIS IN Y-Z PLANE)								
5	5.03	9.27	9.28	.03	−.73	−5.72	5.78	RESIDG
	5.03	9.28	9.28	.03	−.72	−5.72	5.77	RESIDT
Y-AXIS (GENERAL ROTATION)								
$\alpha = 87°$ $\beta = 5°$ $\delta = 86°$	1.24	9.37	10.15	−3.76	−.63	−4.85	6.16	RESIDG
	1.24	9.39	10.15	−3.76	−.61	−4.85	6.16	RESIDT

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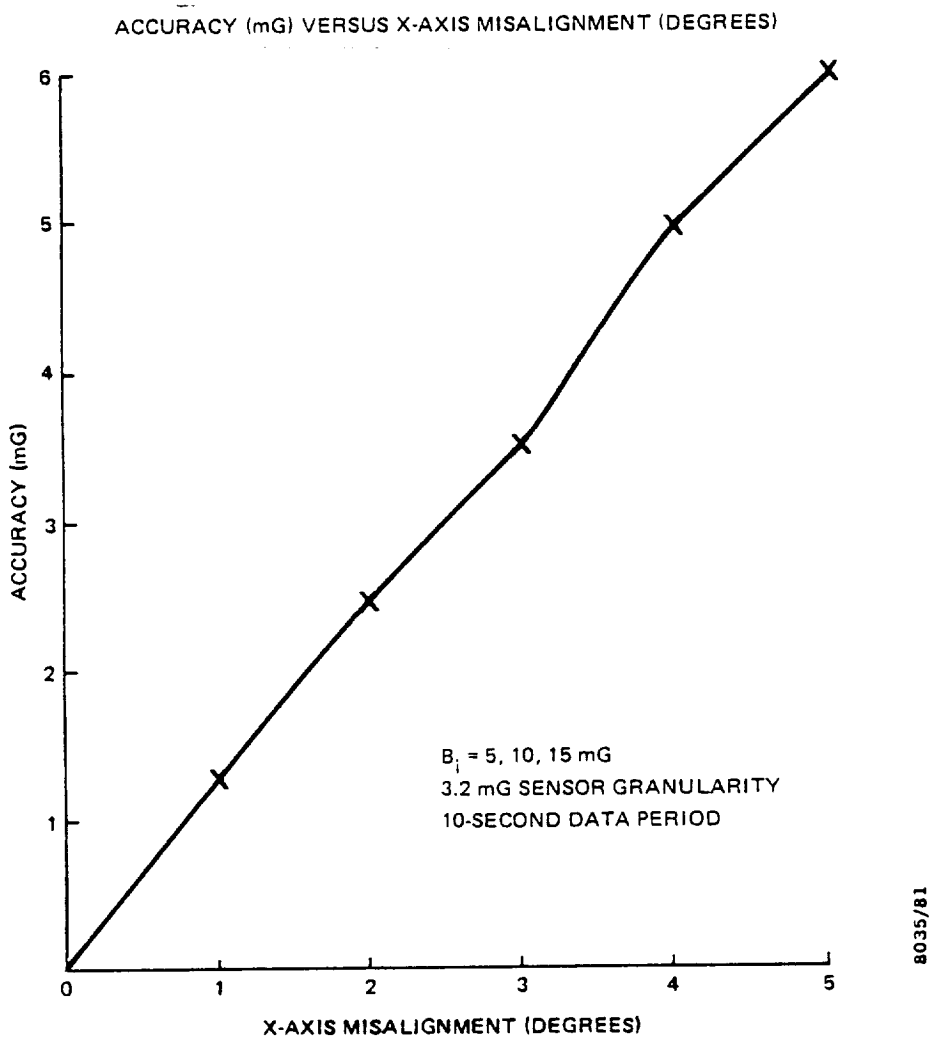

Figure 6-10. Computed Accuracy Versus X-Axis Misalignment

SECTION 7 - CONCLUSIONS

On the basis of this study, several conclusions are presented.

7.1 SENSITIVITY TO DATA PERIOD

Selection of a "good" data period for the CCE magnetometer data readings is the single most critical factor in obtaining accurate magnetometer bias determination results. The accuracy of the results is more sensitive to data period than any other effect (i.e., sensor granularity, magnetometer bias, or sensor misalignment).

In the tests for sensitivity to data period (using data periods ranging from 6 to 42 seconds in increments of 2 seconds), the accuracy oscillated over an order of magnitude. The worst-case data period is equal to the spin period of the spacecraft plus multiples of the spin period (in this case, 6 seconds + n • 6 seconds, n = 0, 1, 2...). The best-case data period would be such that successive magnetometer readings are taken when the spacecraft has rotated π radians (180°) relative to the previous reading (e.g., a 9-second data period plus multiples of 6 seconds). (See Figures 6-1 through 6-5).

7.2 SENSITIVITY TO SENSOR GRANULARITY

Bias determination accuracy does depend somewhat on sensor granularity, but not as much as on data period. Figures 6-1 through 6-5 illustrate that the general trend is toward less accuracy as the granularity increases; however, for good data periods (minimums of the oscillations), the values of the accuracy were excellent (about 1 mG or less) even for granularities as high as 14 mG.

A granularity of 5.0 mG or less is recommended for the AMPTE mission. Good results were obtained for granularity values

of 1.6 mG, 3.2 mG, and 5.0 mG, even when a poor data period (6 or 12 seconds) was used (Figure 6-8). Large errors may occur if the sensor granularity is large, particularly if a poor data period is chosen.

7.3 SENSITIVITY TO MAGNETOMETER BIASES

High magnetometer biases (e.g., up to a 40, 60, 80 mG, x, y, z bias vector), in general, do not seem to be a significant problem for the RESIDG and RESIDT algorithms used in this study, particularly when the data spans perigee. For the sensor granularities of 1.6 mG through 14.0 mG, the results (Figures 6-1 through 6-5) indicate that higher bias magnitude (e.g., a 40, 60, 80 mG bias vector) results in only slightly worse accuracy than a lower bias magnitude (e.g., a 5, 10, 15 mG bias vector). For the above cases, data period is a far more important effect than magnetometer bias. For data taken substantially away from perigee (e.g., 1 hour or more), high magnetometer bias does result in poor accuracy; however, utilization of data that far away from perigee is not recommended.

7.4 SENSITIVITY TO PERIGEE PROXIMITY

For the AMPTE mission, it is recommended that the major data collection period be confined to a window of about $\pm$25 minutes from perigee, the region in which the principal component of the geomagnetic field is about 50 mG or greater (Figure 5-2). Figure 6-9 illustrates that good results may be obtained as much as 40 minutes away from perigee, if the bias magnitude is not high. However, good results (an accuracy of about 1 mG) were obtained for both the high and low magnetometer bias cases for the data taken within 25 minutes of perigee.

7.5 SENSITIVITY TO SENSOR MISALIGNMENT

The effects of misalignment of the x- and y-axis magnetometers are significant. In the range simulated (0 to 5 degrees), an error of about 1 mG resulted per each degree of misalignment.

7.6 RECOMMENDED BIAS DETERMINATION ALGORITHM

For small magnetometer biases (e.g., a 5, 10, 15 mG bias vector), the RESIDG and RESIDT algorithms performed roughly the same qualitatively. Both algorithms show the oscillatory behavior described above as a function of data period. For larger magnetometer biases (e.g., a 40, 60, 80 mG bias vector), RESIDG gives significantly better performance than does RESIDT (Figures 6-7 and 6-9). However, for good data periods, both RESIDG and RESIDT perform well even when large biases are present.

The recommended bias determination algorithm is to use the RESIDT iteration method with the option to use the RESIDG trial solution. For large biases the RESIDG initial bias estimate is more accurate than that used by RESIDT. However, RESIDT was found to be more stable than RESIDG. There were no cases found in this study in which RESIDT diverged. RESIDG did diverge in several cases where large magnetometer biases were present.

7.7 NECESSITY FOR SIMULTANEOUS DATA READINGS

Because the CCE spacecraft is rotating, it is necessary that the three readings from the magnetometer triad be obtained simultaneously for use with the magnetometer bias determination algorithms tested in this study. This requires either that the three readings occur simultaneously in the telemetry data, or that each of the readings be accurately time-tagged such that all three readings can be rotated to a common time using the known spin rate.

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